The Effect Of Distribution Systems On Household Drinking Water Quality In Addis Ababa, Ethiopia, and Christchurch, New Zealand

A thesis submitted in partial fulfilment of the requirements for the Degree of Master of Water Resource Management at the University of Canterbury

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Abstract

Access to clean and safe drinking water is a fundamental human requirement. However, in many areas of the world natural water sources have been impacted by a variety of biological and chemical contaminants. The ingestion of these contaminants may cause acute or chronic health problems. To prevent such illnesses, many technologies have been developed to treat, disinfect and supply safe drinking water quality. However, despite these advancements, water supply distribution systems can adversely affect the drinking water quality before it is delivered to consumers. The primary aim of this research was to investigate the effect that water distribution systems may have on household drinking water quality in Christchurch, New Zealand and Addis Ababa, Ethiopia. Water samples were collected from the source water and household taps in both cities. The samples were then tested for various physical, chemical and biological water quality parameters. The data collected was also used to determine if water samples complied with national drinking water quality standards in both countries. Independent samples t-test statistical analyses were also performed to determine if water quality measured in the samples collected from the source and household taps was significantly different.

Water quality did not vary considerably between the source and tap water samples collected in Christchurch City. No bacteria were detected in any sample. However, the pH and total iron concentrations measured in source and tap water samples were found to be significantly different. The lower pH values measured in tap water samples suggests that corrosion may be taking place in the distribution system. No water samples transgressed the Drinking Water Standards for New Zealand (DWSNZ) MAVs. Monitoring data collected by the Christchurch City Council (CCC) was also used for comparison. A number of pH, turbidity and total iron concentration measurements collected by the CCC in 2011 were found to exceed the guideline values. This is likely due to structural damage to the source wells and pump-stations that occurred during the 2011 earthquake events. Overall, it was concluded that the distribution system does not adversely affect the quality of Christchurch City's household drinking water.

The water quality measured in samples collected from the source (LTP) and household taps in Addis Ababa was found to vary considerably. The water collected from the source complied with the Ethiopian (WHO) drinking water quality standards. However, tap water samples were often found to have degraded water quality for the physical and chemical parameters tested.

This was especially the case after supply interruption and reinstatement events. Bacteria were also often detected in household tap water samples. The results from this study indicate that water supply disruptions may result in degraded water quality. This may be due to a drop in pipeline pressure and the intrusion of contaminants through the leaky and cross-connected pipes in the distribution network. This adversely affects the drinking water quality in Addis Ababa.

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Table of Contents

List of Tables

List of Figures

Abbreviations

AAWSA: Addis Ababa Water and Sewerage Authority

AU: African Union

AC: Asbestos Cement

B.S: The wider Bole subcity

CCC: Christchurch City Council

CFU: Colony Forming Unit

DWSNZ: Drinking Water Standards of New Zealand

DCI: Ductile Cast Iron

E.C: Electric Conductivity

EKHCDP: Ethiopian Kale Heywet Church Development Program

FC: Faecal Coliform

GD: Gefersa Dam

GTP: Gefersa Treatment Plant

HDPE: High-density polyethylene

ICP-MS: Inductively Coupled Plasma Mass Spectrometry

IGAD: Intergovernmental Authority for Development

KT: Kotebe Terminal

LTP: Legedadi Treatment Plant

DL: Detection Limit

Max: Maximum

MAV: Maximum Acceptable Limit

MF: Membrane Filter

Min: Minimum

MFE: Ministry for the Environment of New Zealand

NTU: Nephelometric Turbidity Units

NGOs: Non-Governmental Organizations

N: Number of Samples

PE: Polyethylene

PVC: Polyvinyl Chloride

R: Reservoirs

RC: Residual Chlorine

TC: Total Coliform

W-6: Woreda-6

W-8: Woreda-8

WHO: World Health Organization

1. INTRODUCTION

1.1. Drinking Water, Distribution Systems and Associated Problems

Safe drinking water is one of the basic requirements for human health, development and wellbeing (Khallaf *et al.*, 2014). Water plays a fundamental role in economic growth, poverty alleviation, food security and the protection of ecosystems. However, its natural quality is affected by many biological and chemical contaminants originating from sources such as industry, agrochemicals applied at the catchment level and inadequate collection and disposal of household wastes. Ingestion of these chemical and biological contaminants in drinking water can cause both acute and chronic health problems.

The failure to provide safe drinking water puts public health at risk (Massoud *et al.*, 2010). Contaminated water can serve as a vector for disease transmission and cause human health issues unless it is treated and made safe to drink. For this reason, many technologies have been developed to treat, disinfect and supply safe drinking water. However, treating and disinfecting the drinking water to relevant standards at a treatment facility does not always ensure that the water is safe when it arrives at a household tap.

Providing safe drinking water can improve hygiene and reduce disease. However, water supplied from an old and degraded supply infrastructure is vulnerable to the intrusion of contaminants and may contribute to both endemic and epidemic waterborne diseases (Moe & Rheingans, 2006). The physical, chemical and microbial quality of the drinking water may be degraded in the distribution system as a result of poor environmental conditions and a degraded water supply infrastructure.

Moe and Rheingans (2006) stated water quality degradation can be severe in developing countries. This may be caused by poor sanitation conditions, a degraded water supply infrastructure and inadequate resources to maintain the infrastructure. In order to supply safe drinking water to household residents, the pipelines that supply the water must be kept in a maintained and sanitary condition.

Access to safe drinking water and hygienic living conditions is a global concern and these issues are especially serious in developing countries. Developing countries like Ethiopia have suffered from a lack of safe drinking water and inadequate sanitation services (Amenu, 2013). Nygård *et al.* (2007) has stated that despite the improvements in the water quality leaving water treatment facilities, contamination often occurs within the water distribution infrastructure. Common causes include cross-connected pipelines, water backflow and low/negative pipe-pressure events. There are many causes for negative pipe-pressure and the intrusion of contaminants. Examples include: turning pumps on and off; power failure; pipe maintenance; and supply disruption.

It is believed that piping water to people improves water quality. However, in reality the water supply infrastructure may not provide a reliable supply of safe water to drink. The main issue, which is common in many developing countries, is an intermittent water supply which results in low pipe-pressure and the intrusion of contaminants from the environment where hygiene standards can be very poor (Kumpel & Nelson, 2013).

According to Ainsworth and Water (2004), the drinking water supply infrastructure is just as important as the water treatment facilities in the provision of safe drinking water. However, water supply systems are usually complex and are buried underground. This can make them difficult to operate and maintain if damage occurs. The integrity of the water supply distribution system can breached due to a number of internal or external pipeline problems. Examples includes: pipeline breaks; repair jobs; cross-connections; and backflow events. This can lead to the intrusion of contaminants and change the physical, chemical and biological properties of the treated water.

The combination of poor water supply infrastructure and unhygienic environments can result in the degradation of treated water before it reaches the customers household tap. The aim of this study was to characterise the effect of the water supply distribution system on household drinking water quality in two different cities: Christchurch, New Zealand and Addis Ababa, Ethiopia.

1.2. Drinking Water Quality Parameters Affected by Distribution

Drinking water quality may be analysed by testing a variety of different parameters. The measurements collected provide information on the condition of the water where the samples are collected. As there are many variables that can be measured, which can be both expensive and time consuming, it is important to choose the appropriate tests that are both feasible and effective.

It is important to first characterise the water being tested and the environmental conditions of the area before choosing which water quality parameters to test. This study aims to characterise water quality degradation that may be occurring in water distribution systems in Christchurch, New Zealand and Addis Ababa, Ethiopia. For the purposes of this study, the following physical, chemical and microbial parameters have been chosen:

1.2.1. pH

The pH of a solution is a measure of its acidity or alkalinity. There are currently no health-based guideline values for pH. However, the pH can strongly influence the quality of water by affecting other water quality parameters. For example: the disinfection efficiency of water may be reduced with irregular pH values; and a lower pH may cause pipeline corrosion and further pipeline failure and contaminant intrusion. High or low pH values in drinking water may therefore cause human health problems. They may also have other effects on water quality including changes in taste, odour, and appearance. The pH is an important indicator of pipeline corrosion and chlorination efficiency in a water supply. The World Health Organisation recommends that the pH of drinking water is in the range of 6.5–8.5 (WHO, 2003d).

The World Health Organisation has stated that water with low pH results in higher rates of corrosion in water supply pipelines (WHO, 2003d). The acidic nature of the drinking water can degrade or corrode the internal metal surfaces of the distribution pipelines. This can lead to increased iron concentrations in the drinking water. Unusual changes in the pH level after treated water has entered into the distribution system may indicate water quality deterioration in the distribution infrastructure.

1.2.2. Electrical Conductivity

Conductivity is a measure of a material/substances ability to conduct an electric current. In water, conductivity is effected by the presence of dissolved inorganic solids such as chloride, nitrate, sulphate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminium cations (ions that carry a positive charge). Pure water is poor in electric conductivity. Water that contains large concentrations of dissolved solids can have significant electric conductivity values (Chapman *et al.*, 1996).

Inorganic solids are found naturally in soils and rock materials and can contribute to higher electrical conductivity in water. Significant changes in water conductivity can occur in water distribution systems. This could be caused by the intrusion of environmental contaminants into the distribution system. Sewer lines, storm water and industrial wastes that are not appropriately managed are possible sources of contamination. An increased conductivity may also be attributed to the corrosion of metallic materials used in the distribution system (Payment *et al.*, 2003).

1.2.3. Turbidity

Turbidity is a measure of the clearness or cloudiness of a water sample. As stated by the World Health Organisation, the turbidity of household drinking water can be affected by suspended and colloidal materials. These particles may be present in the treated water due to inadequate filtration within the treatment plant. Increased turbidity may also be caused by: sediment contamination from the external environment; the intrusion of particles associated with industrial and municipal wastes; the growth of biofilms; or the precipitation of corroded metals within the distribution system (WHO, 2006).

The World Health Organisation has reported that there is no health-based guideline value for turbidity. However, turbidity values of less than 5 NTU are usually acceptable to consumers. High levels of turbidity can adversely affect the efficiency of disinfectants. The particles in the water can act as a host for microorganisms and protect them during treatment. Turbidity is therefore an important water quality parameter that should be tested frequently and can provide information regarding potential contamination of water within distribution systems (WHO, 2008).

1.2.4. Nitrate (NO_3) and Nitrite (NO_2)

Nitrate and nitrite contamination in surface and groundwater can be caused by the application of nitrate fertilizers in farming areas. Excess fertilizer can be flushed into the surface water or can leach into the groundwater. The leaching of wastewater, storm-water runoff and other environmental wastes (particularly human and animal effluent) into water supply distribution systems can also contaminate household drinking water with nitrate and nitrite (WHO, 2011).

According to the Pakistan Environmental Protection Agency (2008), the natural concentrations of nitrate in surface and ground water should be relatively low unless they are contaminated from agricultural lands. However, elevated nitrate and nitrite concentrations in drinking water may also be caused by the contamination of water supplies by nitrate/nitrite contributing contaminants. Mechenich and Andrews (1993) stated that elevated nitrite and nitrate concentrations measured in household tap water may indicate contamination of the distribution system by sewage, industrial or municipal wastes.

1.2.5. Total Zinc (Zn)

Zinc is an essential element that is found in all foods and potable waters and is an essential nutrient. There are currently no health based guideline values for zinc concentrations in drinking water. However, elevated zinc concentrations can lead to an unacceptable taste in drinking water. For this reason, the upper guideline value set by the World Health Organisation is 5.0 mg/L (WHO, 2011).

Naturally occurring zinc concentrations do not generally exceed 0.01 mg/L and 0.05 mg/L in uncontaminated surface water and groundwater, respectively. However, elevated zinc concentrations can be found in household water. This can be attributed to the corrosion of zinc that is used to coat galvanized pipelines that are often used in water supply distribution systems (WHO, 2011).

1.2.6. Total Iron (Fe)

According to the South African Water Quality Guidelines published by the Department of Water Affairs and Forestry (1996), iron is the fourth most abundant element on Earth and constitutes 5% of the earth's crust. The World Health Organisation states that as iron is an

element that is essential to bodily function, there are currently no health based guidelines for iron concentrations in drinking water (WHO, 2011). However, excess iron concentrations in drinking water can stain laundry and produce a bitter, astringent taste. For these reasons, the upper guideline value for iron in drinking water is 0.3 mg/L (Ontario, 2003; WHO, 2008).

The dissolved iron concentrations generally found in unpolluted surface waters range from 0.001-0.5 mg/L (Department of Water Affairs and Forestry, 1996). In groundwater, iron is generally found in its soluble ferrous form (Fe^{2+}). As this water is exposed to the atmosphere, the iron is converted to its ferric form (Fe^{3+}). The ferric iron can make water cloudy or turbid with a reddish brown colour. Fully oxidized iron can form an insoluble precipitate that can make the water turbid and may also cause scaling in low pressure pipelines, pressure tanks and reservoirs (Teunissen, 2007).

According to Bigoni *et al.* (2014), electrochemical reactions take place on the surfaces of pipelines that are in contact with water. This can cause corrosion and the failure of pipelines which can lead to contaminant intrusion and further deterioration of the water quality. Guideline values for metals such as zinc and iron are often exceeded in these conditions.

1.2.7. Residual Chlorine

Chlorine is a powerful oxidant and is effective as a disinfectant due to its ability to oxidize the enzymes of microbial cells and reduce their ability to survive (Bidhendi *et al.*, 2006). Drinking water that is sourced from surface or ground water is often contaminated by microbes. This water is often treated to destroy harmful microorganisms and is an essential process in the supply of safe drinking water. As a result, the World Health Organization recommend as minimum as 0.2 mg/L free residual chlorine in household water to ensure that it is free of harmful microbes (WHO, 2008).

In developing countries, many domestic water supplies are treated with chlorine and maintain a certain concentration of residual chlorine to disinfect potential bacterial contamination within the supply infrastructure (Ecura *et al.*, 2011). Monitoring residual chlorine concentrations within the distribution system can indicate if water quality degradation is occurring. Any rapid deterioration or sudden disappearance of the residual chlorine concentrations can indicate

contamination of the supply. For example, a high demand of chlorine may indicate that bacteria and/or biofilms are present in the distribution system (WHO, 2003a).

Measuring the residual chlorine in water samples is important to ensure safe water is being delivered to consumers. The results can also indicate if the supply is contaminated by microorganisms and other contaminants (WHO, 2011).

1.2.8. Microbial Contamination

Microbial contamination of drinking water is caused by the introduction of bacteria, viruses or protozoa which are collectively known as pathogens. These harmful organisms can originate from a variety of sources such as industrial waste, decayed plant matter, agricultural runoff and human wastes. Although many different pathogens can contaminate drinking water, it is impracticable and too expensive to monitor water supplies for all threats (Ministry of Health, 2008). For these reasons, the general presence of pathogens is normally determined by testing for indicator organisms. Common examples of bacterial indicators include *E. coli* and faecal coliform bacteria. The presence of these bacteria in samples indicates that samples are contaminated by faecal material. *E. coli*, faecal and total coliforms have been chosen to measure microbial contamination in this study.

Escherechia coli (*E. coli*)

E. coli is a type of faecal coliform bacteria that originates in the intestines of humans and animals. Its presence in water provides evidence of faecal contamination which may originate from a human or animal source. The presence of *E. coli* may indicate that other harmful microorganisms are present in the sample (WHO, 2011).

The detection of *E. coli* in household tap water may indicate that animal or human waste has contaminated the water supply. The World Health Organisation recommends that no E. coli bacteria should be detected in 100ml sample of water (WHO, 2008).

Faecal Coliform and Total Coliform

Coliforms are bacteria that are always present in the digestive tracts of humans and animals and are found in their waste. They are also found in plant and soil material. The term ‘total

coliform' refers to bacteria such as faecal coliform and *E. coli* which can be found in soil, decomposed plant material, human and animal wastes. The presence of total coliforms in a water supply indicates some form of contamination from any of these sources (New York State Department of Health, 2011).

According to the New York State Department of Health (2011), quantifying total coliform bacteria in water samples gives an indication of the sanitary conditions of the supply. It is one of the most basic tests for bacterial contamination and is widely used to determine if water supplies are contaminated by a faecal or environmental source.

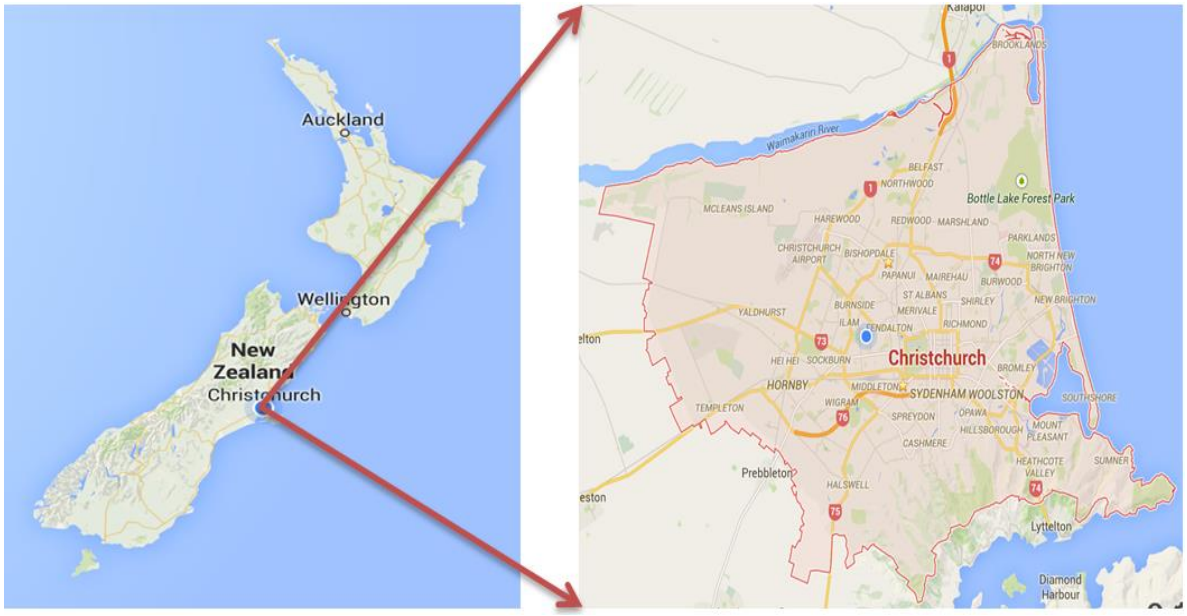
According to the South African water quality guidelines, total coliform bacteria are often used to evaluate the efficiency of drinking water treatment plants and the integrity of the water supply distribution system (Department of Water Affairs and Forestry, 1996). The presence of coliform bacteria in treated water suggests inadequate disinfection. If household tap water contains coliform bacteria, this may indicate post-treatment contamination and/or microbial growth in the distribution system.

1.3. Christchurch City Water Supply

1.3.1. Location of Christchurch City

Christchurch is the largest city in the South Island of New Zealand and is the country's third-most populous city. It has a total land area of 1,426 km² and a population of 457,400 people (Canterbury Earthquake Recovery Authority, 2012). Christchurch is located at 43º 51' S, and 172º 65' E (Figure 1.1).

In summer, temperatures can rise up to 30-35°C. In winter, temperature may drop as low as -10°C. The average annual rainfall is approximately 640 mm which is distributed relatively evenly throughout the year (Donovan *et al.*, 1992).



Source: Developed from Map data ©2015 Google

Figure 1.1: Map and location of Christchurch City, New Zealand

1.3.2. Drinking Water Supply in Christchurch City

Christchurch City has very pure drinking water that originates from the upper reaches of the Waimakariri River catchment. It then proceeds to pass through gravel aquifers of the Canterbury Plains. This gravel has been deposited over millions of years by rivers carrying sediment from the erosion of the Southern Alps (Environment Canterbury Regional Coucil, 2010).

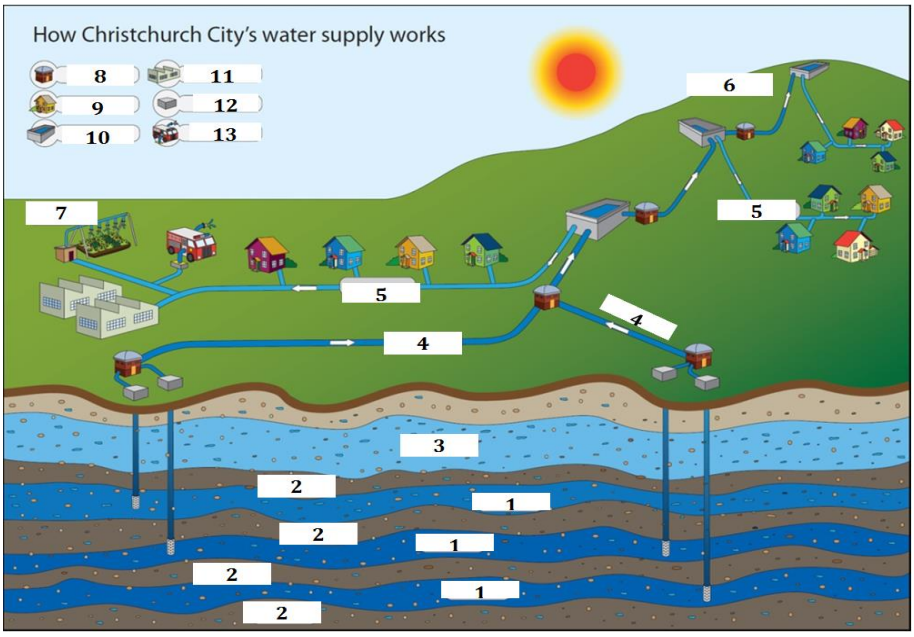
Groundwater that flows through these natural aquifers provides a safe drinking water supply for Christchurch City. This water is extracted and directly supplied to the residents of Christchurch without any need for treatment. The city is renowned for having one of the best drinking water quality supplies in the world (Christchurch City Council, 2012).

Christchurch City's residential and commercial water users are supplied from nearly 150 wells, eight main storage reservoirs, 37 service reservoirs and 26 secondary pumping stations. The storage reservoirs provide water in the event of an emergency and also assist in meeting the peak demands within the Port Hills distribution zone. The water supply mains that carry the water are typically placed underneath roads. To ensure an efficient and uniform water supply

to all distribution zones, the supply wells and pumping stations are uniformly distributed throughout the city (Christchurch City Council Infrastructure Design Standard, 2010).

According to information provided by the Christchurch City Council, water is supplied from a number of wells. The city is split up into a number of different water supply zones including: Central; North West; Rocky Point; Riccarton; and Brooklands. Different wells and pump stations are also used to supply water to these zones.

A diagrammatic representation of Christchurch's water supply system is provided in Figure 1.2. The topography of the city is variable. To ensure that there is equal water supply throughout the city, water is delivered using a pressurized system. Groundwater is initially pumped from wells around the city and is boosted by pump stations up to reservoirs at a higher ground. The water is then distributed to households and industries (Christchurch City Council, 2012).



Source: Figure adopted from Christchurch City Council (2012)

Figure 1.2: Christchurch's drinking water supply system. (1-Aquifer, 2-Aquaclude or Clay impermeable layer, 3-Groundwater, 4-Main supply lines, 5-Local water pipes, 6- Port Hills, 7-Garden irrigation, 8-Pump stations, 9-Private house, 10-Reservoir, 11-Commercial/Industrial, 12-Wellhead and 13-Fire service water supply.

The materials used in Christchurch's drinking water supply system include pipes made of galvanized steel, asbestos-cement (AC), cast iron, ductile iron, polyethylene (PE) and high-density polyethylene (HDPE).

1.3.3. Sanitation and Solid Waste Management in Christchurch City

Christchurch has a high standard of sanitation within the city. This is partly due to effective household waste management practices. Household waste is collected using three different rubbish bins labelled with red, green and yellow lids. The red bin is used to collect non-recyclable and non-organic rubbish. The green bin is to collect organics such as food and garden waste. The yellow bin is used to collect recycling wastes such as paper, cardboard, glass, metal and plastic containers. These wastes are collected weekly by the Christchurch City Council (CCC) and by private and commercial operators. It is taken to the regional landfill which is located in Kate Valley for disposal (Figure 1.3).

The Ministry for the Environment of New Zealand (MFE) implemented the Waste Minimisation Act in 2008 to encourage the reduction in the amount of waste generated and disposed of in landfills. The aim of this legislation was to reduce the degradation of the environment. As a result, all territorial authorities in New Zealand are working towards implementing the Act. Christchurch City Council states that every person has a responsibility for the waste they generate. Every business centres, industries and institutions are required to act in accordance with the Act. This results in little waste being left uncollected on the streets, roads and households in Christchurch City. The CCC also provides free support and training to raise community awareness with the aim of keeping Christchurch City tidy today and in the future (Christchurch City Council, 2013).

Source: Photo taken during field

Figure 1.3: A truck collecting solid waste from a kerbside in Christchurch City. This photo shows that the waste management system used by the Christchurch City Council is keeping the city tidy.

1.3.4. Drinking Water Contammination in Christchurch City

Any contamination of the groundwater source would require difficult and time-consuming remediation. For this reason, industrial, commercial and rural activities that could contaminate the groundwater are controlled under Environment Canterbury's Natural Resources Regional Plan (Environment Canterbury Regional Coucil, 2010). The aquifers used for drinking water are highly protected and less prone to contamination. Christchurch's domestic water supply is considered to be reliable, affordable and not a health risk for the residents.

However, Christchurch suffered serious earthquakes in 2010 and 2011. After the earthquakes, many residents of the city were concerned that the wells, wastewater and water supply distribution systems would be damaged which could contaminate the supply. As a result, chemical, biological and physical tests were conducted by the CCC to test if water quality was degraded. The results indicated this was the case and mitigation strategies such as boiling drinking water notices and temporary chlorination plants were implemented at the time.

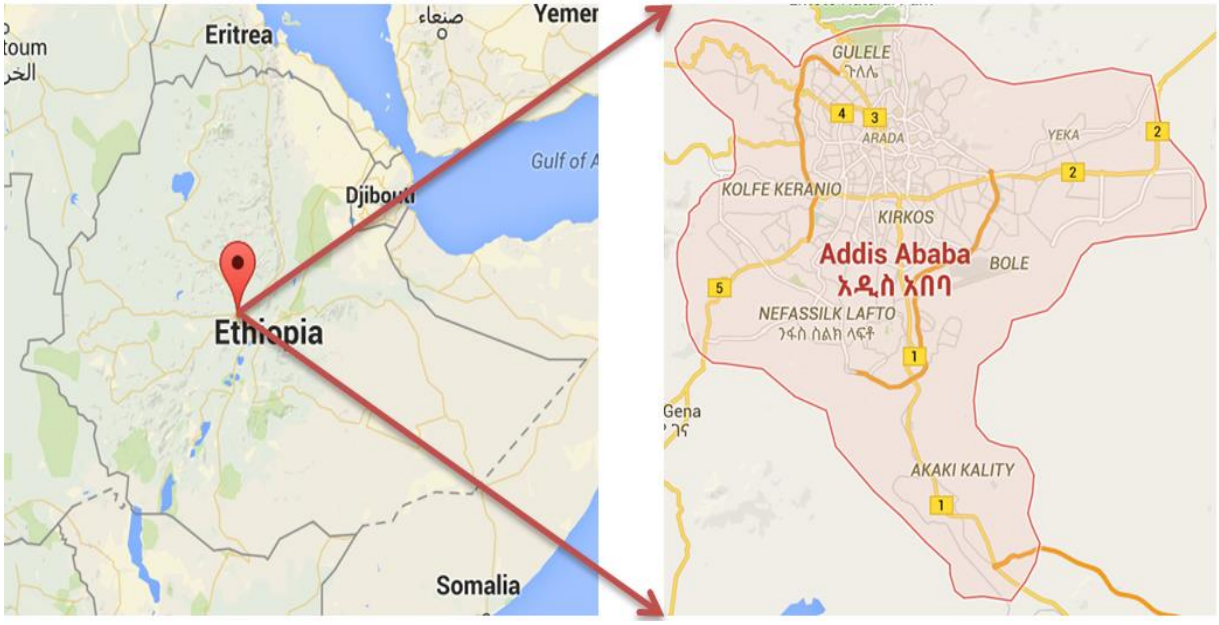
In Christchurch City, drinking water contamination caused directly by anthropogenic activities and lack of sanitation is unlikely. Christchurch City residents have enjoyed the high quality drinking water provided without any treatment required to meet New Zealand Drinking Water Standards (Christchurch City Council, 2011). However, it is possible that the water supply distribution network could affect the water quality from source to household. To date, few studies have been conducted to test this possibility.

1.4. Addis Ababa City Water Supply

1.4.1. Location of Addis-Ababa City

Addis Ababa is the capital city of Ethiopia. It is located in the centre of the country between 8º55'and 9º05'N latitude and 38º40' and 38º50'E longitude and has an area of 540 km^2 (Figure 1.4). Its altitude ranges from 2000-2800 meters above sea level (Regassa *et al.*, 2011).

The city's temperature generally ranges from 9.9-22.7^{0}C and has 1205.2 mm of average annual precipitation. It has three distinct seasonal periods. The seven months between March and September are a wet period. The short rain season occurs between March to May, while the main rain season occurs during the months of June to September. The dry season occurs during the months of October to February (Hailu, 2011).



Source: Developed from Map data ©2015 Google

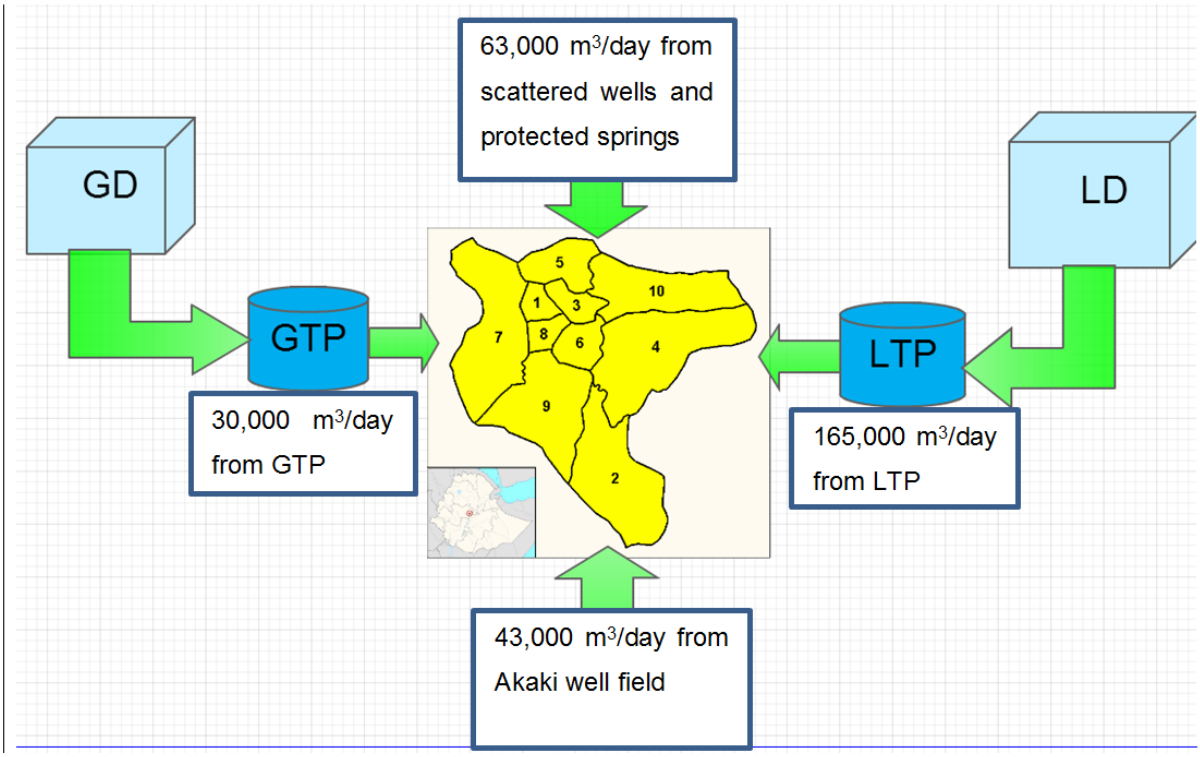
Figure 1.4: Map and location of Addis Ababa City, Ethiopia.

More than 3 million residents are distributed over the 10 subcities located in Addis Ababa (Hailu, 2011). As the nation's capital, Addis Ababa is the economic, political and administrative hub of Ethiopia. Addis Ababa is also the headquarters for the African Union (AU), Intergovernmental Authority for Development (IGAD) and numerous other regional and international organizations. The city therefore has an important role in Ethiopia and Africa. However, much like other cities in the developing world, Addis Ababa has a number of public health problems such as a lack of access to safe drinking water, inadequate sanitation and poor environmental conditions (UN-HABITAT, 2008).

1.4.2. Drinking Water Supply in Addis Ababa City

A number of dams have been constructed to source water for the growing city of Addis Ababa. The first dam (Gefersa-I) was constructed in 1944. In the 1960's the Gefersa treatment plant (GTP) was constructed and had the capacity to treat 30,000 cubic meters of water per day (m^3/day). In 1966 another dam (Gefersa-III) was built both to increase the drinking water storage capacity and also to function as a sediment trap. After water is treated at the GTP, two pipelines carry water to distribution reservoirs located in Addis Ababa. The Legedadi Dam, the Legedadi treatment plant (LTP) and the supply pipeline was constructed in 1970. During the 1980's the LTP's capacity to treat water was increased from 50,000 m^3/day to 150,000 m^3/day. With the construction of the additional Dire dam, the LTP can today supply up to 165,000 m^3

of drinking water per day. An additional drinking water supply in Addis Ababa is the Akaki well field. These wells can supply up to 43,000 m^3/day (Elala, 2011).



Source: Author

Figure 1.5: Addis Ababa's drinking water is sourced from surface waters collected from the Legedadi dam (LD) and Gefersa dam (GD). Groundwater is sourced from the Akaki well field and other scattered wells and protected springs within the city.

Approximately 14% of the water supplied to Addis Ababa is provided by the Akaki well field which is located about 10 km south of Addis Ababa. A further 21% (63,000 m^3/day) of the water is sourced from scattered wells and protected springs within the city. The remaining 65% (195,000 m^3/day) is provided from the Legedadi dam (LD) and Gefersa dam (GD) (Elala, 2011).

The Gefersa I and III dams are located about 20 km northwest of Addis Ababa. Water from these dams is distributed in the northwest parts of Addis Ababa. The Legedadi and Dire dams are located about 30 km northeast of Addis Ababa. Water from these dams is distributed in the

eastern and central parts of the city. The southern area of Addis Ababa is supplied water from the Akaki well field source which is located in the area (Figure 1.5).

Initially, groundwater from the Akaki well field is pumped into storage reservoirs. Depending on the waters background quality, it may be first disinfected in the reservoirs before it is pumped into the distribution system for public use. In general, all water sourced from these wells is disinfected manually by the addition of powdered chlorine (as shown in Figure 1.6) (Birhanu, 2007).

Source: Birhanu (2007)

Figure 1.6: The general disinfection process for water supplied from wells in the city of Addis Ababa.

Rapid population growth and a lack of maintenance and new water treatment facilities has lead in to water shortages in Addis Ababa. These shortages particularly affect the residents of low income areas of the city. The majority of slum dwellings have limited access to water. It is thought that approximately 34% of the residents get water from public taps which have an intermittent supply of water. As much as 35% of the supplied water is wasted by leakage of

pipelines. Giving water supply priority to industries has also contributed to the water shortage in the city (UN-HABITAT, 2008).

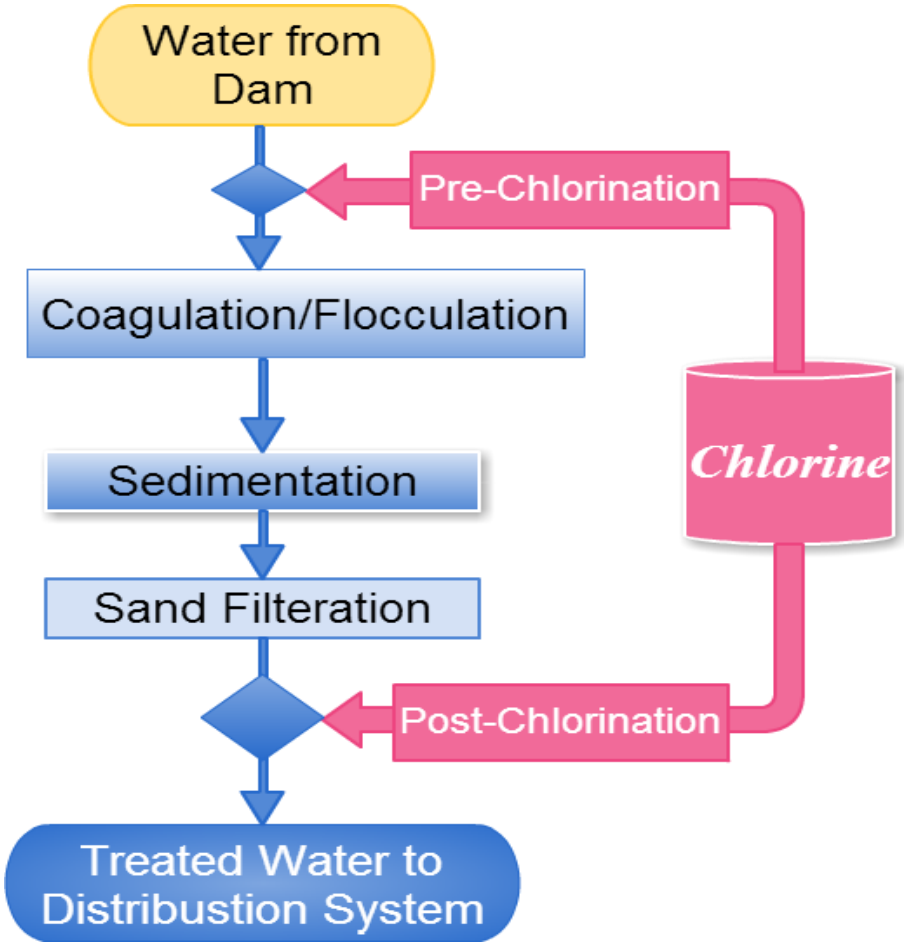
Ndaruzaniye (2011) has previously described the water governance in Addis Ababa as being in a very poor state. The population of the city has grown from two to approximately four million in the last fifteen years. In the same period, the area of the city has also expanded from 220 to 540 square kilometres. Capital investment in water supply infrastructure and sanitation services has not kept up with this growth. As a result, there is now pressure on the Addis Ababa City Administration and the Addis Ababa Water and Sewerage Authority (AAWSA) to expand their services and provide safe drinking water supply and sanitary conditions.

The growth of Addis Ababa City has been unregulated and unstructured and the city has not had formal urban planning until recently. This has put many constraints on the water supply system. A major concern is the significant losses of water caused by leakage from the 40 year old supply infrastructure (Elala, 2011).

A previous study has suggested that as much of half of the water supplied to Addis Ababa is lost from the distribution system before it reaches consumers. The main reported reasons for these losses are pipe leakages and breakages caused by age related degradation of the distribution system. There is also a lack of money available to replace these aged pipes (Desalegn, 2005).

1.4.3. Operating System of Legedadi Treatment Plant (LTP)

All residents of the study areas obtain their drinking water from the Legedadi dam (LD). This structure retains the surface water harvested from a wider catchment of small rivers located in Legedadi dam area. The catchment is known for its intensive agricultural farming practice. As a result, the household drinking water is treated at LTP before supplied directly. The level of water inside the reservoir varies seasonally. Depending on the level of water at a time, raw water is delivered to the treatment plant using three intake valves placed at different vertical positions. As summarized in Figure 1.7, the LTP uses treatment processes such as pre-chlorination, coagulation/flocculation, sedimentation, sand filtration and post-chlorination.



Source: Author

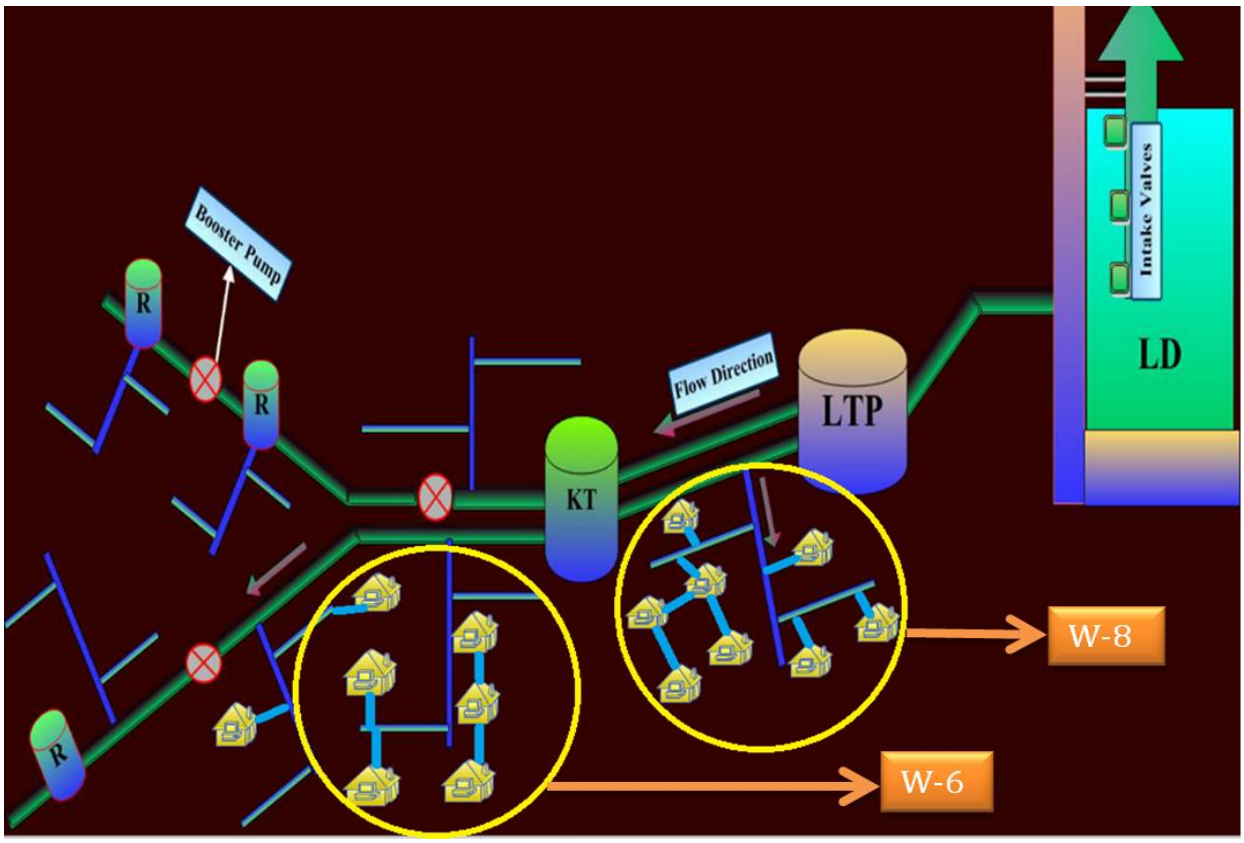
Figure 1.7: Scheme detailing the Legedadi Water Treatment Plant operating system

Pre-chlorination is applied to the raw water as it enters the treatment plant. The main function of this process is to kill and reduce bacterial load. It also prevents the growth of algae inside the treatment plant.

Coagulation chemicals are used in the coagulation/flocculation process. Polyelectrolyte is used as a primary coagulant. Polydiallyldimethylammonium chloride (PolyDADMAC) and lime are used as coagulant aids. The main function of the primary coagulant is to neutralize the electrical charges of the suspended particles in the raw water. This causes particles to flocculate. The coagulant aid is used to increase the density of particles and enhance the sedimentation process. After floc formation, the heavy particles settle to the bottom of sedimentation compartment. The clear water next moves to a filtration compartment where water is passed through different

size sand filters. Post-chlorination is applied after filtration to maintain free residual chlorine that disinfects bacterial contamination that may enter the supply network.

Figure 1.8 summarises how the drinking water is delivered to customers after being treatment at the LTP. The treated water is transported from the LTP by two (900mm diameter) ductile cast iron (DCI) transmission pipelines. Water is delivered to areas in close vicinity, such as Woreda-8, before arriving at the Kotebe terminal (KT). Depending on the topographic nature of the distribution zones, water from the Kotebe terminal is pumped to reservoirs (R) located at elevated areas of the city. Water is then distributed by gravity.



Source: Author

Figure 1.8: Diagrammatic representation of the water supply system from Legedadi Treatment Plant (LTP). W-8 is directly connected to the supply, whereas W-6 receives its source after treated water stored in Kotebe terminal (KT)

1.4.4. Sanitation and Solid Waste Management in Addis Ababa City

A study by Regassa *et al.* (2011) previously stated that rubbish collection in Addis Ababa is not standardized for different areas of the city. Collection bins are only located on popular main roads. Households usually use a variety of temporary rubbish storage containers including baskets, cardboard boxes, cans, plastic bags and barrels.

Source: Photo taken during field

Figure 1.9: Photographs of kerbside rubbish collection taken in W-8 and W-6 in Addis Ababa. The waste collection in W-8 is hygienic and organised. Waste disposal in W-6 is uncontrolled.

Figure 1.9 shows examples of the different ways waste is disposed of in Addis Ababa. Most household waste is collected using two wheeled containers that are operated manually. These are then transported to trucks which take it to a landfill.

It is estimated that Addis Ababa produces 765 tons of solid waste per day. Only 65% of this waste is collected and disposed of in the landfill. The remained 35% may remain in various areas of the city such as: in the streets; empty areas; in sewer and drainage lines; and dumped

on the river banks of the city (UN-HABITAT, 2013). This solid waste pollutes water in these environments (Figure 1.10).

Source: Photos taken during field

Figure 1.10: Uncollected solid wastes degrade the environment and reduce the sanitary conditions of the city. (A) Solid waste trapped by a pipe crossing a river (B) Solid waste left uncollected.

Addis Ababa has been declared as one of the worst cities in Ethiopia in terms of environmental sanitation conditions and hygiene practices (UN-HABITAT, 2008). It has been approximated that 26% of the houses and the majority of slum dwellings have no toilet facilities. Rivers, ditches and open spaces are usually used as defecation sites. A study by Abay (2010) has also previously reported that as much as 25% of the population have no access to sanitation services. Shared pit latrines may be used by up to 75% of the population in the city and only 0.6% of the population used modern flush toilets connected to a sewer system. It was suggested that only 0.6% of the total sewage produced was reaching the wastewater treatment plant. The remainder is likely to be leaching through the soil and polluting waterways. Waste from pit latrines can directly pollute the groundwater which is used as a drinking water supply. The waste can also seep into unsecure water supply pipelines and can contaminate household water.

Ndaruzaniye (2011) has previously stated that the city's sanitation facilities and services are among the lowest in Sub-Saharan Africa. Only 12% of households in Addis Ababa have flush toilets that discharge to sewers or septic tanks. The greatest proportion (63%) of households uses individual or shared pit latrines. The remaining 25% do not have access to sanitation facilities. The incidences of disease are greatest in the densely populated areas where water supply and sanitation services are particularly inadequate.

Cities that do not have adequate wastewater networks and management practices will have issues with supplying safe drinking water. In Addis Ababa, the majority of houses and business centres (such as hotels, garages and car washes) dispose of their grey-water into the drainage systems. However, these drainage systems are ineffective in many areas. During the wet season, solid wastes mixed with rainfall can flow into cross-connected water supply systems (Figure 1.9 and Figure 1.10). This can contaminate household drinking water.

1.4.5. Drinking Water Contammination in Addis Ababa

Addis Ababa has grown very rapidly since it was founded in 1886. This growth has put enormous pressure on water supply services and the sewerage system. The water supply infrastructure in the city is up to 40 years old and is known for its low output capacity and high water losses due to degraded pipelines (Desalegn, 2005).

Source: Photo taken during field

Figure 1.11: The nature of the water distribution infrastructure in most old dwellings. The red arrows indicate pipelines crossing drainage ditches.

The drinking water produced in Addis Ababa is generally safe and meets the national drinking water standards (Ethiopia Ministry of Water Resources, 2002). The national drinking water standards are identical to the World Health Organisation's (WHO, 2008) guideline for the provision of safe drinking water. However, the treated water is generally delivered to households in old metallic (galvanized iron and cast iron) pipelines. Some piping has been replaced by HDPE and PVC materials. Pipes are either buried underground or exposed to the environment. In many of the slum dwellings, the pipelines are very old and degraded. Approximately 30-40% of the drinking water supplied to the city does not reach consumers, The water is lost at different levels of the distribution system due to leaking pipes and aging infrastructures (Ayenew, 1999; Kabeto, 2011).

The combination of the degraded infrastructure and a cross-connected distribution system may provide a favourable environment for drinking water contamination to occur. Considering the poor environmental conditions in many districts of the city (Figure 1.11), there are many

opportunities for drinking water contamination in cracked and leaky water supply pipes. Currently, there is no comprehensive water quality monitoring or data for drinking water quality at the household level. It is therefore unclear how much contamination is occurring to the drinking water quality once it is distributed from the treatment plants, and whether the water is safe to drink once it reaches the households.

1.5. Aims and Objectives of this Research

The main objective of this research was to determine the effect of distribution system on households' drinking water quality of two contrasting cities, Christchurch, New Zealand and Addis Ababa, Ethiopia. Hence, this research study has provided information on the effect of distribution systems on drinking water quality of both Christchurch and Addis Ababa Cities.

The study in Christchurch was conducted on randomly selected households where their taps are connected to the nine municipal pump stations/wells (Picton, Jeffreys, Auburn, Central, Avonhead, Tara, Wrights, Sydenham and Addington) for which monitoring data could be obtained from Christchurch City Council (CCC).

The study in Addis Ababa City was conducted on two specific districts of Bole subcity namely: Wereda-6 and Wereda-8, and also the wider Bole subcity itself. Wereda-6 is among the old districts which is occupied and dominated by slum dwellers, and the nature of water supply distribution system is very old with poor waste management system as shown in Figure 1.9, Figure 1.10 and Figure 1.11. Wereda-8 is occupied by wealthy residents with modern and improved water supply infrastructures.

The specific objectives of the research were;

- To measure and analyse the selected physical (pH, conductivity and turbidity), chemical (nitrate, nitrite, iron, zinc and residual chlorine), and biological (*E. coli*, faecal and total coliform) household drinking water quality parameters at source and households of both cities (LTP, Woreda-8, Woreda-6 and the wider Bole subcity (B.S) of Addis Ababa City, and wells or pump stations and households taps of Christchurch City).

- To compare the analysed water quality results between selected study areas (between LTP, and Woreda-8 and Woreda-6 tap waters of Addis Ababa City, and between wells or pump stations and households taps of Christchurch City) and examine if the distribution system affects the water quality.
- To compare the analysed physical, chemical and biological parameters of household drinking water quality of Addis Ababa and Christchurch City with the Ethiopian (WHO, 2008) drinking water quality standards and New Zealand Drinking Water Standards, respectively.

2. RESEARCH METHODOLOGY

2.1. Households Drinking Water in Christchurch City

2.1.1. Selection and Description of the Study Area

Christchurch City's naturally pure drinking water is sourced from deep, confined and semi-confined aquifers which originate from the upper reaches of the Waimakariri River catchment. Contamination of this groundwater would require difficult and time-consuming remediation. Therefore industrial, commercial and rural activities that could damage this resource are controlled under the Environment Canterbury's Natural Resources Regional Plan.

The drinking water which is supplied to the wider Christchurch City does not require treatment to meet the New Zealand Drinking Water Standard. However, it is possible that the water supply distribution network could affect the water quality from source to household. Therefore, the quality of water was determined in samples collected from municipal pump-stations and household taps.

2.1.2. Sample Collection

Water samples were collected from nine municipal water supplies pump stations/wells for which monitoring data could be obtained from Christchurch City Council (CCC).

A total of 27 water samples were also collected from taps in randomly selected households of Christchurch City. Samples were collected between April and May and later between mid-November and mid-December.

At Source/Well

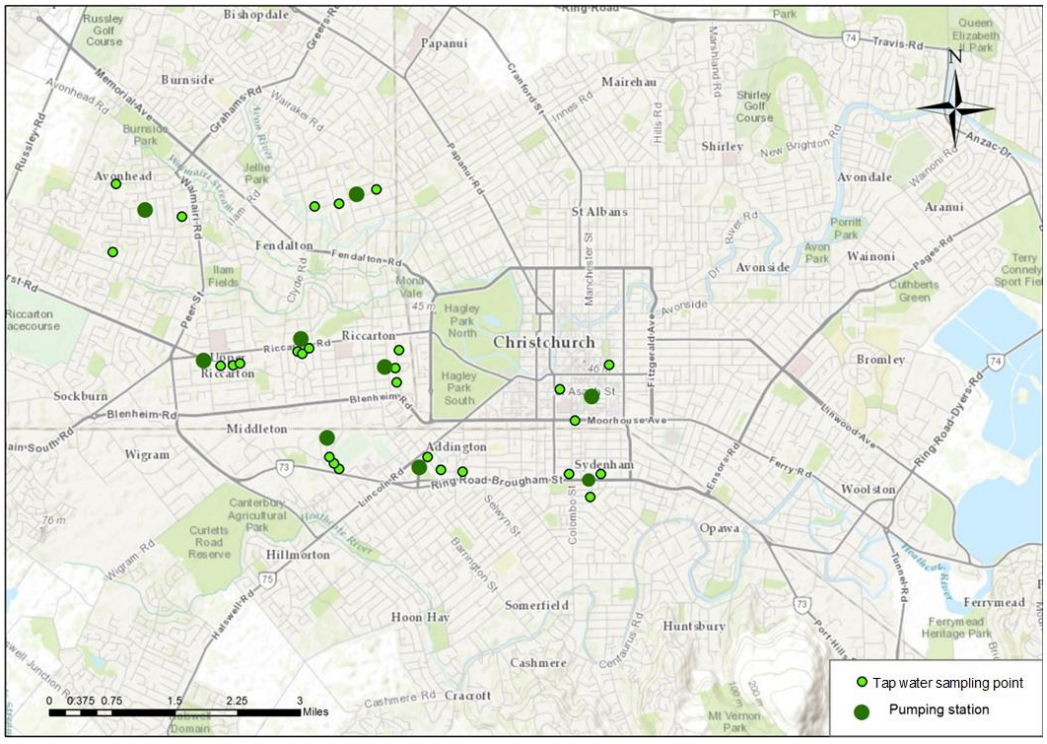
Due to safety and security issues, public wells/pump stations are not permitted to be sampled by individuals outside CCC. However, physical, chemical and biological water quality results for the chosen nine pump stations (Picton, Jeffreys Auburn, Main Pumps, Avonhead, Sydenham, Tara, Addington and Wrights) were obtained from CCC.

The monitoring data obtained from CCC is available for the years 1985-2014. However, the most recent data between 2010 and 2014 was used for comparison with the households' tap water quality data. A total of 26 data points were chosen.

At Household Taps

Tap water samples were collected from 27 randomly selected households which are connected to one of the nine municipal pump stations (Figure 2.1). Samples were analysed for concentrations of nitrate (NO_3), nitrite (NO_2), total zinc, total iron, turbidity, *E. coli* and faecal coliform. Tap water was collected into 50ml plastic centrifuge test tubes which were pre-washed with deionized water in the laboratory. Tubes were rinsed three times with the target water before samples were collected.

Samples for analysing both nitrate and nitrite, water samples were filtered through a 0.45µm membrane to prevent any chemical reactions between reagents and suspended materials that may be found within the samples. Samples for total zinc and total iron were preserved using pure concentrated (8 Molar) nitric acid (HNO_3).



Source: ESRI (2015)

Figure 2.1: Location of sampling points in Christchurch City, New Zealand

2.1.3. Sample Analysis

Water samples were immediately taken to the Lincoln University Waterways Laboratory Centre for analysis. The water quality parameters were analysed and the analytical details of the methods are described below:

pH and Conductivity

For household water samples, the pH and conductivity were measured using a portable HACH HQ40D digital multi-meter.

Turbidity

Turbidity is a measure of the clarity of the water. It is a measurement of the amount of suspended particles that make water turbid or hazy. In this study, the turbidity of water samples was measured using a HACH DR/890-Portable Colorimeter. This functions by passing light through the sample and measuring the amount of light scattered by the presence of suspended materials within the sample.

Nitrate (NO_3) and Nitrite (NO_2)

For analysing nitrate (NO_3) and nitrite (NO_2), water samples were filtered using a 0.45 µm membranes clipped into the tip of MS®PES syringes and collected into 50ml plastic centrifuge test tubes. Samples were analysed using a HACH DR/890 portable colorimeter. Following the Hach Company (1997-2009) cadmium reduction method number 8039 for nitrate and diazotization method number 8507 for nitrite, 10ml samples were prepared on vials, and NitraVer® 5 Nitrate and NitriVer® 3 Nitrite reagent powder pillows were also used to analyse nitrate and nitrite, respectively.

Total Iron and Total Zinc

Total iron and zinc was analysed in unfiltered, acidified water samples by Hill Laboratories in Hamilton. Metal concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS) (APHA 3125 B 22nd ed. 2012) method.

Free Residual Chlorine

Christchurch's household drinking water is supplied from groundwater which does not require chlorination. Free residual chlorine was not analysed for Christchurch City water samples.

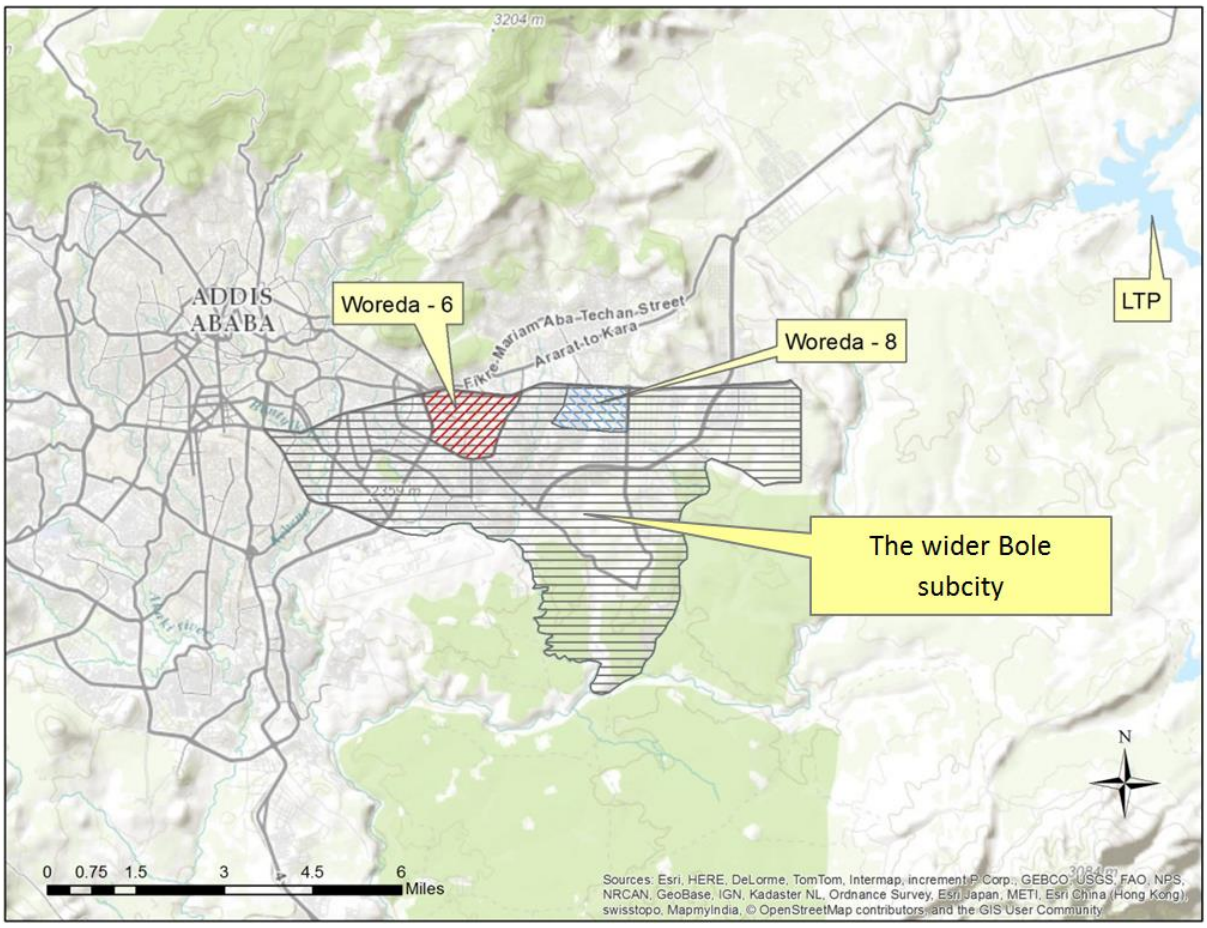
Microbiological Parameters

For measuring *E. coli* and total coliform bacteria concentrations, water samples were collected in 50ml plastic centrifuge tubes before being transported to the Waterways Laboratory at Lincoln University. Upon arrival, 1 ml of sample water was pipetted onto the bottom centre of a 3M™ Petrifilm™ count plate that contains the culture media for growing bacteria. Culture media was incubated for 24 hours at 37.4^{o} Celsius. Finally, after 24 hours of incubation, blue and red colonies of bacteria with associated gas bubbles were counted. Blue colonies were counted as *E. coli*. The sum of both blue and red colonies was used as a measure of faecal coliforms.

2.2. Household Drinking Water in Addis Ababa

2.2.1. Selection and Description of the Study Areas

Two key study areas within Bole subcity and wider Bole subcity itself were chosen for water quality analysis. The two study areas, Wereda-6 and Wereda-8 are located within the subcity of Bole, an eastern part of Addis Ababa (Figure 2.2). According to the City Government of Addis Ababa (2012), the subcity has an area of 122 km^2 with a total population of 328, 900 and a population density of 2,694 per km^2. 26,500 and 21,147 people live in Wereda-6 and Wereda-8, respectively.



Source: ESRI (2015)

Figure 2.2: Study areas of Woreda-8 and Woreda-6 and the wider Bole subcity of Addis Ababa City, Ethiopia. LTP is the Legedadi Treatment Plant which is the source of water collected in the study areas.

The state of the water supply network in Wereda-6 and 8 was provided by a branch manager and senior engineer working for AAWSA the Gurdshola branch. Wereda-6 is among the older settlements and has poor housing. Households often lack toilets. Most water distribution systems are connected beneath the resident's houses or across/along drainage lines which makes inspection and maintenance very difficult during leakage or an event of breakage (Figure 2.3). In contrast, Wereda-8 is a recent development. Housing is modern and has good water supply infrastructure and a hygienic environment.

Source: Photos taken from Woreda-6

Figure 2.3: Water supply pipelines in cross-connection with drainage ditches. (The red arrows indicate pipelines passing through the drainage)

These two districts were chosen as study sites due to their vicinity and contrasting sanitation conditions and age differences in their water supply distribution infrastructure. Other sites within the wider Bole subcity were also used in this study. The data from wider Bole subcity and from the two districts within Bole subcity were also used to assess if the overall households' drinking water quality meets the Ethiopia (WHO) drinking water standards.

2.2.2. Sample Collection

As presented in Table 2.1, the World Health Organisation recommends that a minimum of one sample of water supplied should be tested per month for every 5000 people supplied by a pipeline. Therefore, sample should also be tested for physical, chemical and biological parameters. The approach used for determining the number of samples tested in this study was based on the total number of people within the study areas that are served by the water supply (WHO, 1997). The overall sampling and sample collection procedures for all the physical, chemical and biological parameters tested in this study were also based on the World Health Organisation recommendations.

Table 2.1: Minimum sample numbers recommended for a piped drinking-water distribution system

Population served	Number of monthly samples
<5000	1
5000–100000	1 per 5000 population
>100000	1 per 10,000 population, plus 10 additional samples

Source: (WHO, 1997)

At the Source/Treatment Plant

To characterise the drinking water quality before it enters the distribution system, water samples were collected after treatment at the Legedadi Treatment Plant (LTP). A total of 4 water samples were collected over 3 months. One sample was collected every three weeks between July and September. Samples were analysed for selected physical, chemical and biological water quality parameters.

Water samples were collected using 0.5 litre plastic containers for the analyses of conductivity, turbidity, nitrate (NO_3) and nitrite (NO_2). For the analysis of zinc and total iron, water samples were collected using 50 ml plastic centrifuge test tubes washed with deionized water. These tubes were also rinsed three times with the target water before samples were collected. Water samples were collected in resilient glass bottles for the analysis of both *E. coli* and total coliform. Sufficient sodium thiosulphate was added in each sampling glass bottle to neutralise the chlorine and not to kill the bacteria that may found in the sample. Samples were transported to the Addis Ababa Water Sewerage Authority (AAWSA) or Ethiopian Kale Heywet Church Development Program (EKHCDP) laboratories for analysis.

At the Household Taps

A total of 60 tap water samples were collected from randomly selected households within the study areas of Woreda-6, Woreda-8 and the wider Bole subcity (B.S) (Figure 2.2). Of these samples, 20 were collected from Woreda-6, 20 from Woreda-8 and the remaining 20 samples from the wider Bole subcity (B.S). Samples were collected every three weeks between July and September. Samples were collected in 0.5 litre plastic containers for the analysis of conductivity, turbidity, nitrate (NO_3) and nitrite (NO_2). Water samples were also collected in 50ml plastic centrifuge test tubes for the analysis of total zinc and total iron. Water samples for

analysis of both *E. coli* and total coliform were collected using resilient glass bottles. Sufficient sodium thiosulphate was added in each sampling glass bottle to neutralise the chlorine and not to kill the bacteria that may be found in the sample. Samples were transported to Addis Ababa Water Sewerage Authority (AAWSA) or Ethiopian Kale Heywet Church Development Program (EKHCDP) laboratories for analysis.

2.2.3. Sample Analysis

Samples were immediately analyzed once they were delivered to the Addis Ababa Water Sewerage Authority (AAWSA) or Ethiopian Kale Heywet Church Development Program (EKHCDP) laboratories. Water samples were poured with aseptic technique from the original 0.5 litre bottle into a glass beaker for the measurement of pH and conductivity. The remaining water sample was used for the analysis of nitrate (NO_3), nitrite (NO_2) and turbidity. Samples for total zinc and total iron analysis were preserved using two pipette's drop of nitric acid (HNO_3) per 50ml sample.

pH and Conductivity

For the measurement of pH and conductivity, water samples were collected from the LTP and household taps. Samples were then delivered to the Addis Ababa Water Sewerage Authority (AAWSA) Laboratory Centre for Drinking Water Quality. Upon arrival, each bottle was thoroughly mixed before a sample was poured from each 0.5 litre plastic container into a clean glass beaker which was deep enough to submerge the pH and conductivity measuring probes. A HORIBA-D-50 Series meter was used to measure pH. The conductivity was measured using a Hach Model CO150 conductivity meter.

Turbidity

The turbidity of water samples was measured using a Hach Model 2100AN turbidimeter. Before analysis, sample bottles were inverted several times to resuspend any sedimented particles. The vial used for turbidity analysis was first rinsed with deionized water and then sample water. The vial was then filled with sample water, gently inverted several times and wiped with lint free tissues before being placed into the turbidity meter. The white arrow on the turbidity vial was aligned to the white line on the turbidimeter. Measurements were taken when the turbidity-reading from the readout reaches the maximum and stops.

Nitrate (NO_3) and Nitrite (NO_2)

Both nitrate (NO_3) and nitrite (NO_2) were analysed using a HACH DR/4000U spectrophotometer at the Addis Ababa Water Sewerage Authority (AAWSA) laboratory. Nitrate was measured using the cadmium reduction method (Nitrate HR method 8039). Nitrite was measured using the diazotization method (LR method 8507). The standard methods published in the Hach Company (2005) handbook for water analysis were used. 25ml and 10ml water samples were prepared in sample cells. HACH NitraVer® 5 nitrate and NitriVer® 3 nitrite reagent powder pillows were used to analyse nitrate and nitrite, respectively.

Total Zinc (Zn)

For the analysis of total zinc, acidified water samples were sent to the Ethiopian Kale Heywet Church Development Program (EKHCDP), an NGO private laboratory that works on integrated water and sanitation programmes. Samples were brought to room temperature on arrival and analysed using the Palintest-photometer method. Two 10 ml marked round glass test tubes were rinsed using deionized water. One test tube was filled with a water sample to its 10 ml mark. The second test tube was filled with deionized water for the purposes of an experimental blank.

The Palintest-Photometer method can detect zinc concentrations of 0-4.0 mg/L in natural and treated water samples. The test method suggests dechlorination of samples to prevent bleaching effects and interference of color development during the test. To do this, one zinc-dechlor tablet was crushed and added to the prepared sample to dissolve. Next, one zinc tablet (the reagent chemical) was crushed and added to the sample to dissolve. Samples were then stood for five minutes for complete dissolution and color development. The total zinc concentration was then determined on the Palintest-Photometer 7100 instrument after zeroing with the experimental blank sample.

Total Iron (Fe)

Total iron concentrations were measured using a HACH DR/4000U spectrophotometer. Method 8008 (0.02-3.00 mg/L) from the Hach Company (2005) handbook for water analysis was utilised. Two sample vials were first rinsed with deionized water. The first vial was filed with deionized water for the purposes of an experimental blank. The second was filled with a

water sample. The FerroVer iron powder pillow reagent was next added and swirled to mix. The vials were then left for a three-minute reaction period. An orange colour developed if iron was present in the sample. After this period, the blank sample was placed into the cell holder to zero the instrument. Finally, the test sample was measured. The total iron concentration was recorded as mg/L.

Free Residual Chlorine

Free chlorine is a volatile chemical that can react in samples during the transportation process. For this reason, residual chlorine was analysed directly in the field using a portable test kit that comes with a colour disc comparator. The comparator has a range of interchangeable colour discs. The colours on the disc are proportional to the concentration of residual chlorine present in the sample.

The method uses two test tubes. The first test tube acts as comparator and the second test tube to be used to measure the residual chlorine in the sample. Tubes were rinsed to avoid contamination from previous test. The first tube was filled to its 10ml mark line with sample of water to act as a blank sample and inserted in the left opening of the comparator. The second tube was filled with 10ml sample and one DPD free chlorine reagent powder pillow was added. The sample was swirled to mix. The instant reaction of the reagent produces a red/pink colour if chlorine is present in the sample. After colour development, tube was inserted in the right opening of the comparator and colour disc was rotated until the colour match with established colour standards. Thereby the concentration of free residual chlorine in the sample was recorded in mg/L.

Microbiological Parameters

Initially, *E. coli* and faecal coliforms were proposed to be quantified in this research project. However, the only method available at the Ethiopian Kale Heywet Church Development Program (EKHCDP) laboratory in Addis Ababa was the Coliscan® membrane filter method. This technique simultaneously detects both *E. coli* and total coliforms.

The drinking water samples was analysed using the Coliscan® Membrane filter method. All laboratory equipment including forceps, petri dishes and filter funnel apparatus were first

sterilised with flame heat. The working bench was disinfected using liquid Dettol as described in the EKHCDP laboratory manual.

First, a sterilised pad was placed on a petri dish, and then 2 ml of Coliscan® MF, which is the liquid growth media for bacteria, was uniformly applied on the pad. 100ml sample water was filtered through a 47µm pore size membrane filter. The filter paper was then transferred to the pad on the petri dish that contains the growth media using sterilised forceps. The petri dish was then incubated at 35°C ± 0.5°C for 24 hours.

After incubation for 24 hours, bacterial colonies were identified and counted on the filter with the use of a flush light and 10-15X microscope. This method detects the types of bacteria based on their colour. Colonies with a blue/purple colour development were counted as *E. coli*. The sums of blue/purple and pink colonies were counted as total coliforms.

2.2.4. Data Validation and Laboratory Quality Assurance

Reagents supplied by HACH have a maximum shelf life when stored in a location that is cool, dark, and dry. The effectiveness and shelf life of reagents are likely to be affected if reagents are exposed to high levels of moisture, carbon dioxide, temperature and light. Standard tests should be run to check reagent quality and the accuracy of the measuring instruments (Hach Company, 2005).

To do this, deionized water was bought from a pharmacy for the preparation of reagent blank. This measures the proportion of the result that is contributed by the reagent. All reagents and instruments used in the AAWSA laboratory were tested and checked for their effectiveness using the deionized water (Figure 2.4). All reagent blank results obtained from the instruments in the AAWSA laboratory were very small which was expected from deionized water. An exceptional result was found for the NitraVer® 5 Nitrate reagent powder pillow.

Figure 2.4: Deionized water used to check the effectiveness of instruments and reagent powder pillows in the AAWSA laboratory.

To ensure that cross contamination did not occur during analysis, a negative control was tested during every bacterial analysis. The negative control was prepared by following the same procedure except 100ml sterilised water was filtered and placed on the petri dish that contains the pad socked with growth media. This was then incubated at 35°C ± 0.5°C for 24 hours. The filter was then checked for colony forming units. No bacterial colonies were found in each test round.

2.3. Statistical Analysis

All water quality results were collated and recorded in a MS-Excel worksheet. Descriptive and independent sample t-test statistical analysis was performed. Descriptive statistics, including boxplot, scattered plot and stacked bar graphs, were used to show the overall water quality variation and relationships that occurred between the study areas. The independent samples t-test was performed to determine if the difference of the means of the parameters were significantly different.

2.3.1. Descriptive Statistics

In research it can be difficult to present all raw data and visualise what that data shows. Descriptive statistics can be used to summarize and describe information that has been collected from a study. Then the data can be displayed in a way that is meaningful for explanation. Therefore, descriptive statistics are helpful in showing data variability by highlighting the maximum, minimum, median, mean and standard deviation, which allows the reader to understand and interpret easily.

In this study, maximum, minimum, median and mean values of the raw data were described. These statistical analyses were performed using the Microsoft Excel data analysis tool pack (version 2010).

2.3.2. Independent Samples t-Test Statistical Analysis

The independent samples t-test is an inferential statistical test that is used to compare the means of two samples which come from a different population. This test can determine whether the difference is statistically significant and may help to draw a conclusion about the study. The independent samples t-test was applied to determine the significant differences in mean values of each water quality parameters within the selected study areas. The 95% confidence interval, which is commonly used in scientific research, was utilized. This means a p-value of <0.05 was determined to be statistically significant. This statistical analysis was performed using IBM SPSS (Version 20).

The independent samples t-test statistical analyses mainly work with equal and unequal variance option. The IBM SPSS software calculates both the independent samples t-test and Levene's test for equality of variances at the same time. The output values are generated on the same table. Similarly, the Levene's test for equality of variances also uses a 95% confidence level. The p-value generated was used to determine if the differences in populations mean were statistically significantly different or not.

2.3.3. Graphs

Statistical graphs such as the boxplot, scattered plot and stacked bar graph are among the most important graphical analyses and are essential for visualizing variations among the study sites.

The graphs summarize data points and illustrate what parametric relationships may exist between study sites. These graphs are also useful tools in organizing data points.

Hence, the graphs produced and used in this study include boxplots, scattered plots and stacked bar graphs. These were generated using the Microsoft Excel data analysis tool pack (version-2010) and the IBM SPSS (Version 20).

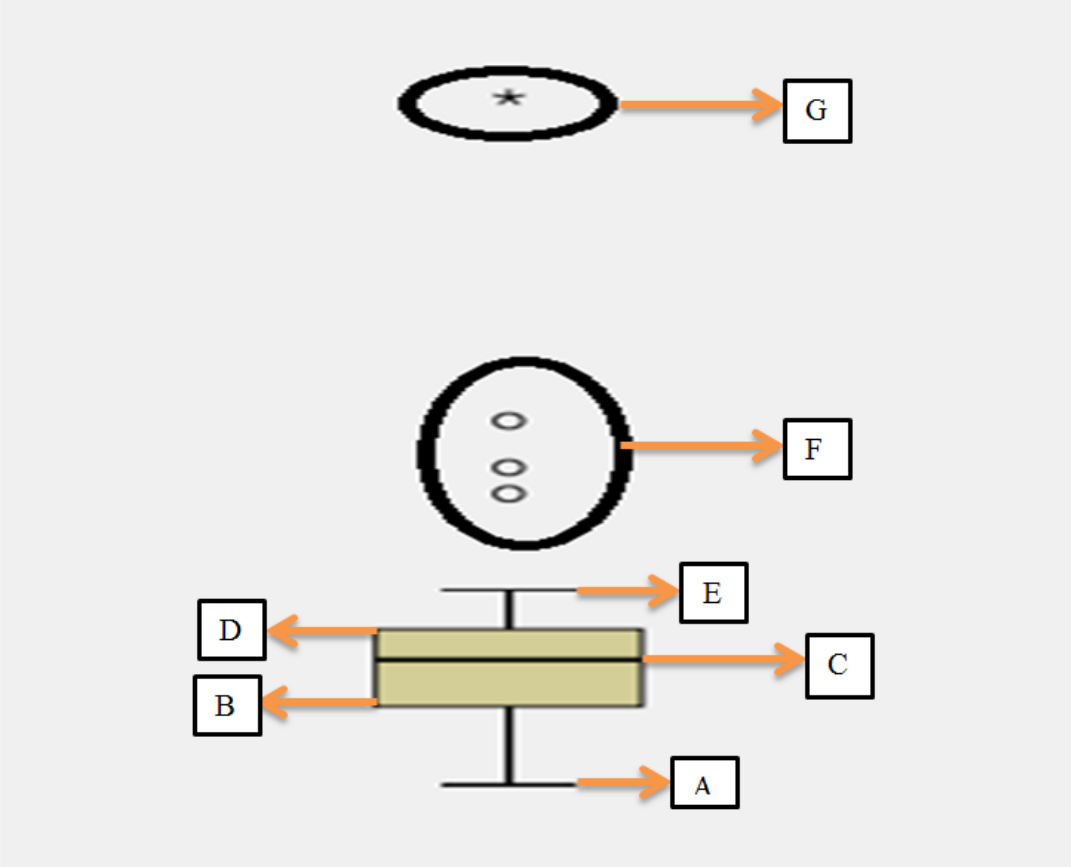


Figure 2.5: Example of boxplot, a type of graph used to display useful descriptive statistical values. The details of the graph are described below.

Figure 2.5 shows an example of a boxplot which is one of the graphs generated in this study. The horizontal line within the box (C) represents the median value of the sample. The lower (B) and upper (D) ends of the box represent the 25^{th} and 75^{th} quartiles, also known as lower and upper quartiles, respectively. The lines extending from each end of the box are called whiskers, and these lines represent the lowest (A) and highest (E) data points used in the analysis. The dot marks within the circles of outside of the boxplot represent the data point outliers (F) and extreme outliers (G) within the sample.

3. RESULTS

The first section of this chapter presents the water quality results of the household drinking water samples collected in Christchurch, New Zealand. The second section presents the results of samples collected in Addis Ababa, Ethiopia. The descriptive statistics and results generated from the independent samples t-test are summarised in tables (from Table 3.1-Table 3.9). These tables, along with boxplots, scattered plots and bar graphs are presented in each sub-section of this chapter. The raw data collected for Christchurch and Addis Ababa along with other supplementary data are attached in Appendices (from Appendix A to Appendix H).

3.1. Christchurch City Household Drinking Water

Water samples were collected from the source and a number of household taps around the city. An assessment of effects was then conducted to determine whether the water distribution infrastructure is affecting the water quality. The water quality results for the source water were obtained from the Christchurch City Council (CCC) drinking water monitoring data.

The independent samples t-test was conducted to determine if significant differences exist between the source and household tap water quality data. The measured and independent samples t-test results are summarised in Table 3.1, Table 3.2 and Table 3.3.

3.1.1. pH

The data produced in Table 3.1 shows the variation of pH levels between the source and household tap water samples. This data can also be visualised in the boxplot in Figure 3.1. The median pH values measured in the source and tap water samples were 7.83 and 7.34, respectively (Figure 3.1). The maximum and minimum pH levels measured in the source water were 8.25 and 6.90, respectively. The maximum and minimum pH levels measured in the tap water were 8.06 and 6.53, respectively.

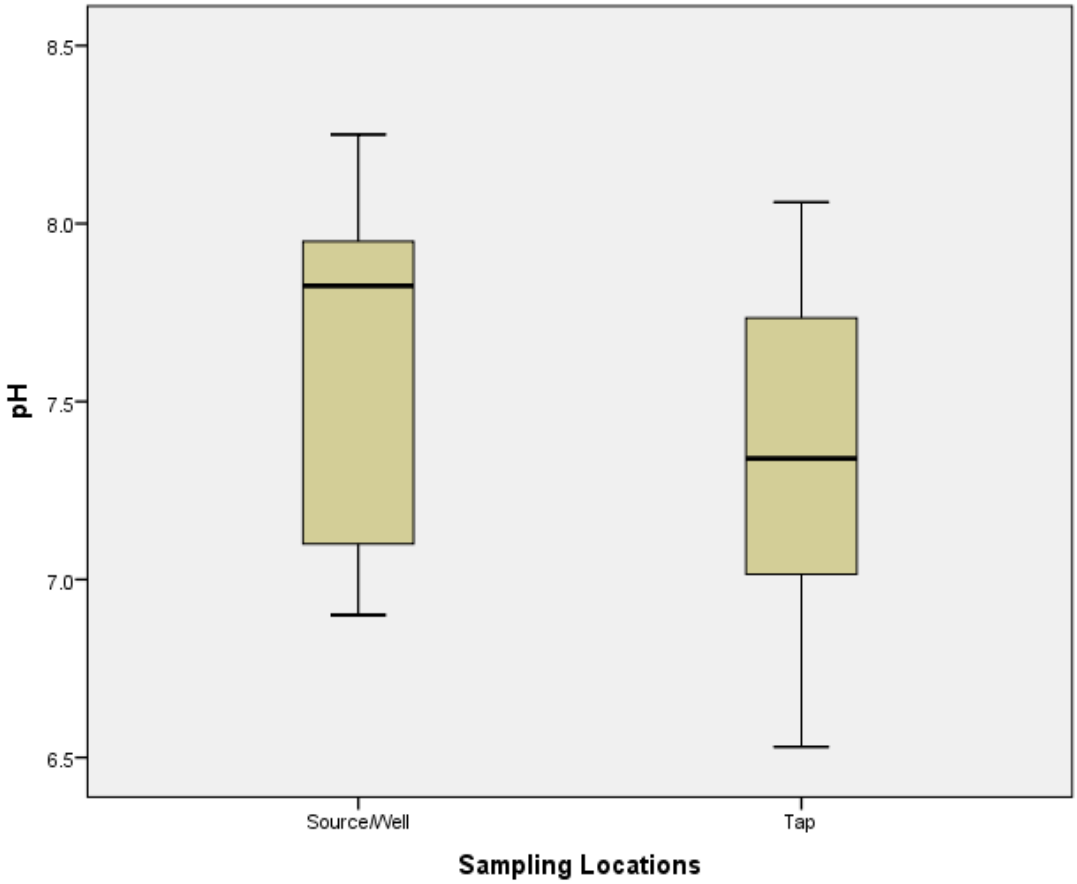


Figure 3.1: Boxplot showing the pH levels measured in source and tap water samples collected in Christchurch.

Similar mean and median pH values were determined in source and household tap water samples (Table 3.1). However, the median values in the boxplot (Figure 3.1) indicate that there is a slight pH variation between the source and household tap water samples. The pH level decreases after the source water enters into the distribution system and travels to the household taps. The independent samples t-test shows that the pH levels are significantly different (*p=0.042*) (Table 3.3).

3.1.2. Conductivity

As shown in Table 3.1, the maximum conductivity values measured within the source and household tap water samples were 323.00 and 221.00 µS/cm, respectively. The minimum values from the source and household tap water samples were 87.00 and 100.40 µS/cm, respectively. The mean conductivity values for the source and tap water samples were slightly different at 139.41 ± 47.37 and 133.09 ± 27.63 µS/cm, respectively. The median conductivity

values were very similar (Figure 3.2 and Table 3.1). The results from the independent samples t-test (Table 3.3) show that the variation in conductivity between the source and household tap water samples was not significant (*p=0.554*).

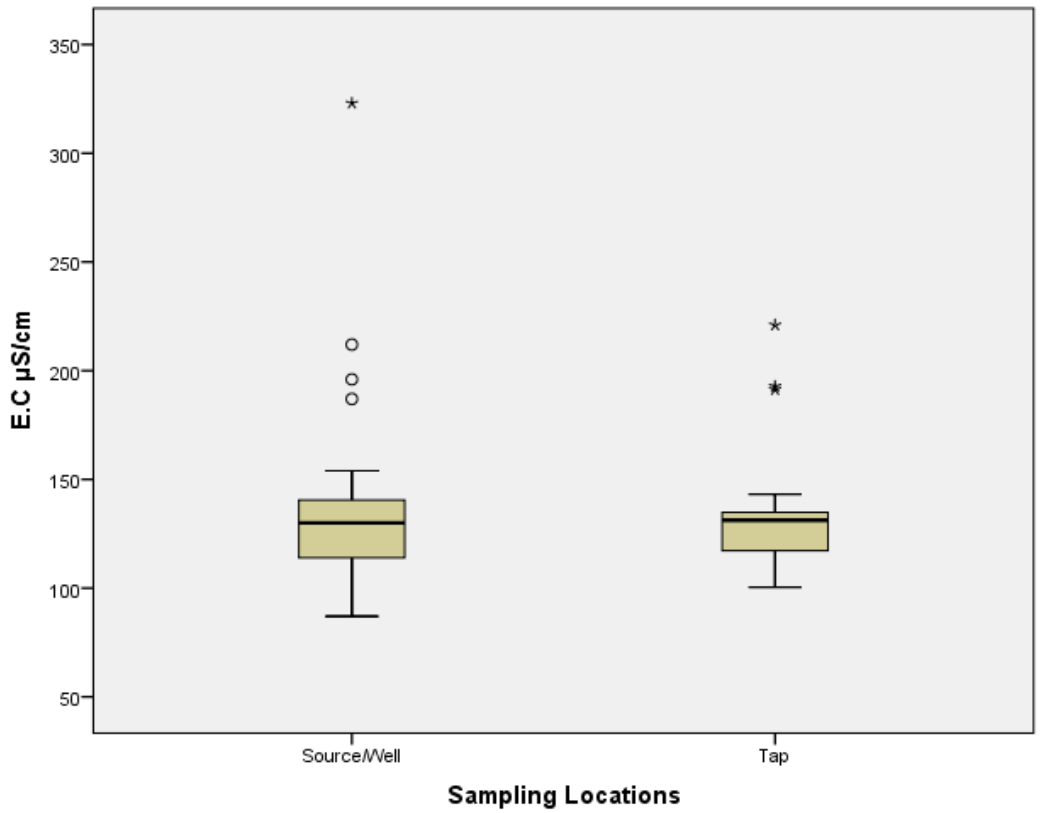


Figure 3.2: Boxplot showing the electrical conductivity (E.C) values measured in source and tap water samples collected in Christchurch.

3.1.3. Turbidity

The maximum and minimum turbidity values measured from the source water were 9.50 and 0.06 NTU, respectively. All turbidity values measured in the household tap water samples were less than 1 NTU (Table 3.1). There were a number of source water samples that were unusually turbid. These are indicated as outliers. However, the median turbidity value calculated from the source water samples was lower than the tap water samples (Figure 3.3). 50% of the source water samples were found to have turbidity less than 0.14 NTU (Table 3.1). 23% of the water samples (N=26) from the source had turbidity values greater than 2.50 NTU.

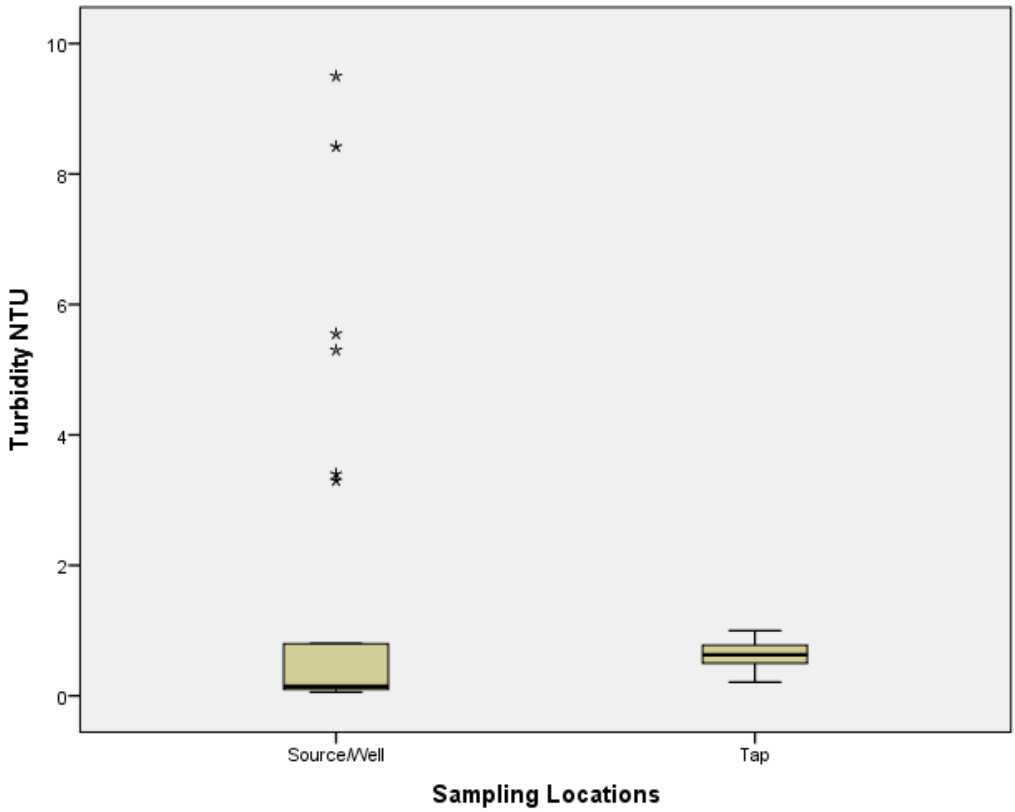


Figure 3.3: Boxplot showing turbidity values measured in source and tap water samples collected in Christchurch.

The bar graph in Figure 3.4 displays the median and mean turbidity values. A higher mean value was found from the source water. A large difference between the mean and median values of the source water was also observed. The mean and median values calculated for the tap water samples were similar (Figure 3.4).

Figure 3.4 indicates that there is little turbidity variation between the source and tap water samples The independent samples t-test determined that the difference was not statistically significant ($p=0.11$) (Table 3.3).

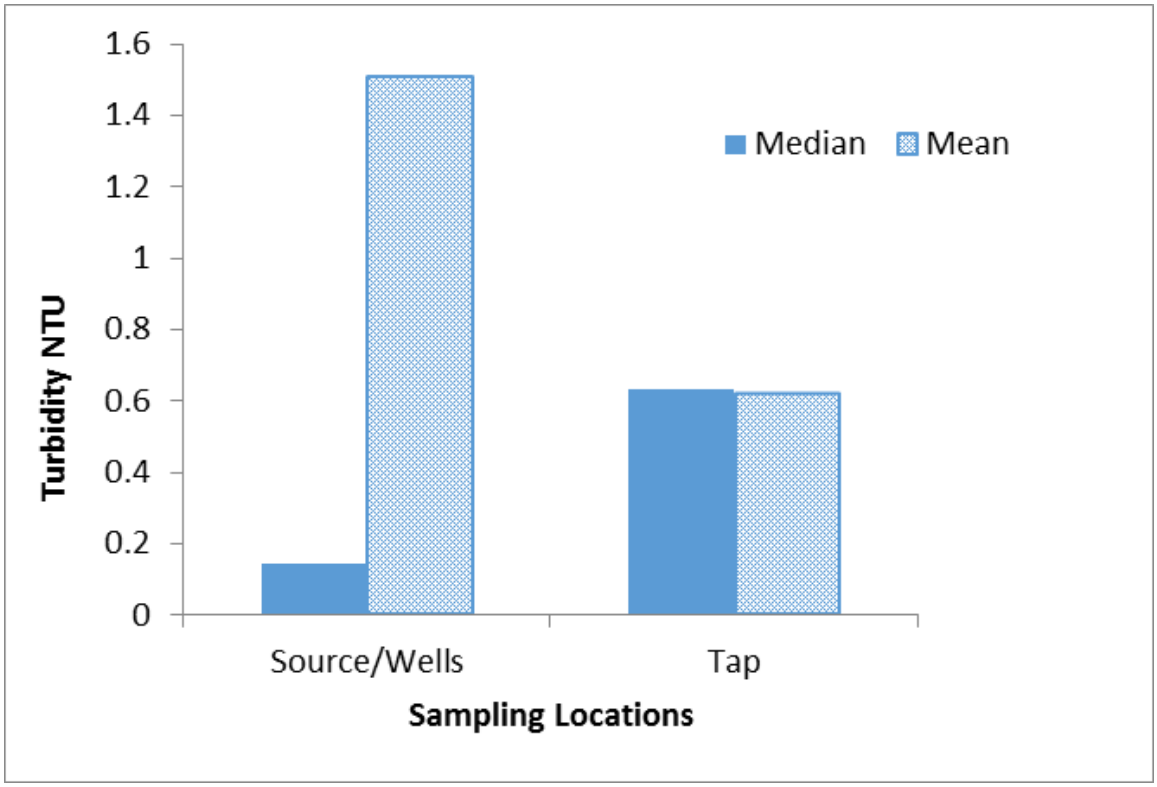


Figure 3.4: The median and mean turbidity values determined in source and tap water samples collected in Christchurch.

Table 3.1: Summary of water quality results for physical parameters measured in source and tap water samples collected in Christchurch, New Zealand.

Parameters	Descriptive Statistic	Sampling location and No. of samples	
		Source (N=26)	Tap (N=27)
pH	Maximum	8.25	8.06
	Minimum	6.90	6.53
	Median	7.83	7.34
	Mean	7.60	7.34
	Std Dev	0.45	0.43
Conductivity (µS/cm)	Maximum	323.0	221.0
	Minimum	87.0	100.4
	Median	130.0	131.2
	Mean	139.41	133.09
	Std Dev	47.37	27.63
Turbidity (NTU)	Maximum	9.50	0.95
	Minimum	0.06	0.21
	Median	0.15	0.63
	Mean	1.51	0.62
	Std Dev	2.72	0.20

3.1.4. Nitrate (NO_3)

The maximum, minimum, median and mean nitrate concentrations measured in the source water samples were 28.73, 0.27, 1.33 and 3.66 ± 5.79 mg/L, respectively, while 11.93, 1.99, 5.75 and 5.81±2.07 mg/L nitrate concentrations were found in the tap water samples, respectively (Table 3.2).

A higher median nitrate concentration was measured in the tap water samples (Figure 3.5). Figure 3.5 and Figure 3.6 both indicate that there was a variation in nitrate concentrations between the source and tap water samples. A higher nitrate concentration was measured in the tap water. However, the independent samples t-test in Table 3.3 demonstrates that the variation was not statistically significant (*p=0.083*).

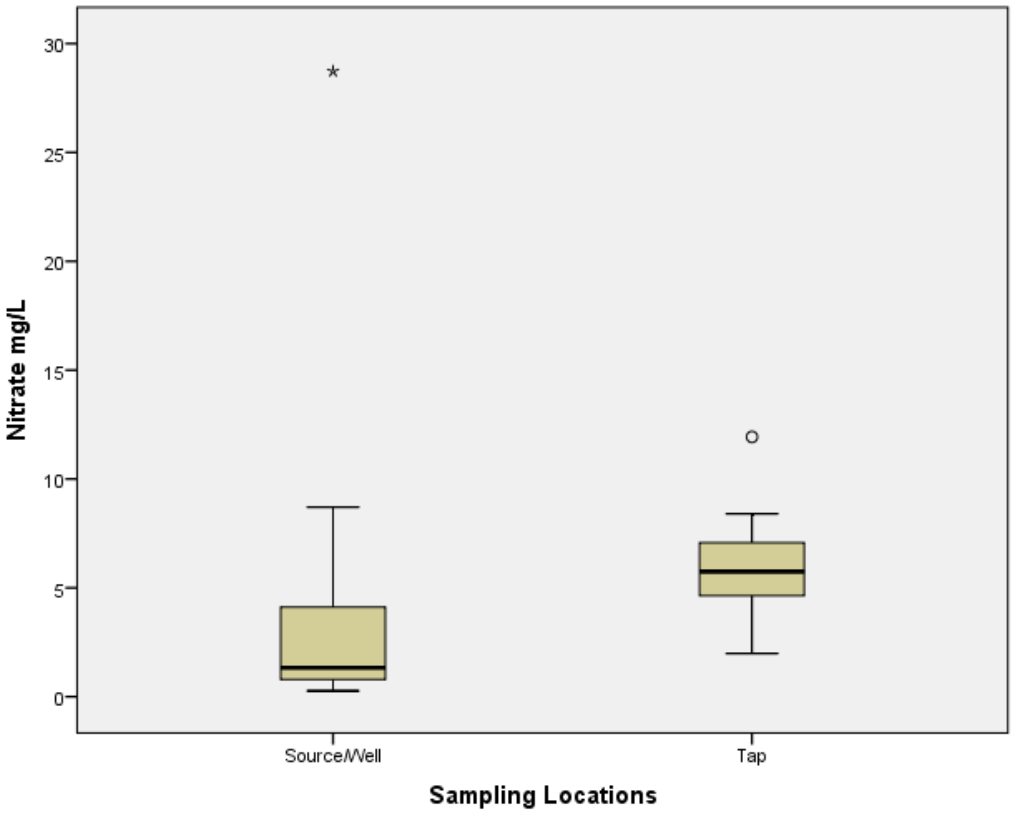


Figure 3.5: Boxplot showing nitrate concentrations measured in source and tap water samples collected in Christchurch.

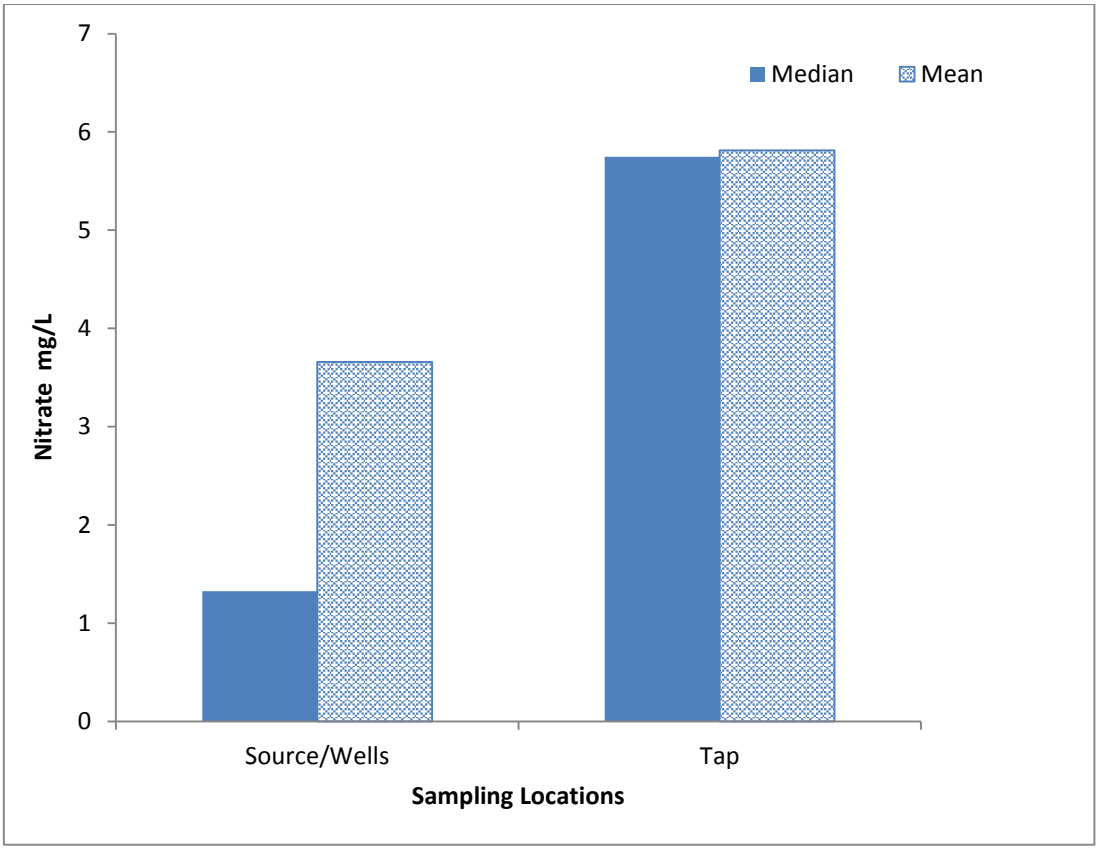


Figure 3.6: The median and mean nitrate concentrations determined in source and tap water samples collected in Christchurch.

3.1.5. Nitrite (NO_2)

Table 3.2 details the nitrite concentrations measured in the source and household tap water samples. Nitrite concentrations varied from 0.017-0.185 mg/L in the source water samples. In the household tap water samples, the nitrite concentrations varied from 0.007-0.059 mg/L. As shown in Figure 3.7 and Figure 3.8, there were a number of high concentrations measured in the source water. These are plotted as outliers. The nitrite concentrations measured between the source and tap water samples were similar.

Figure 3.7 and Figure 3.8 show that the median nitrite concentrations measured in the source and household tap water samples were similar. However, a slightly higher mean concentration was measured in the source water (Figure 3.8). The independent samples t-test confirmed that the nitrite concentrations measured in the source and tap water samples was not statistically significantly different ($p=0.130$) (Table 3.3).

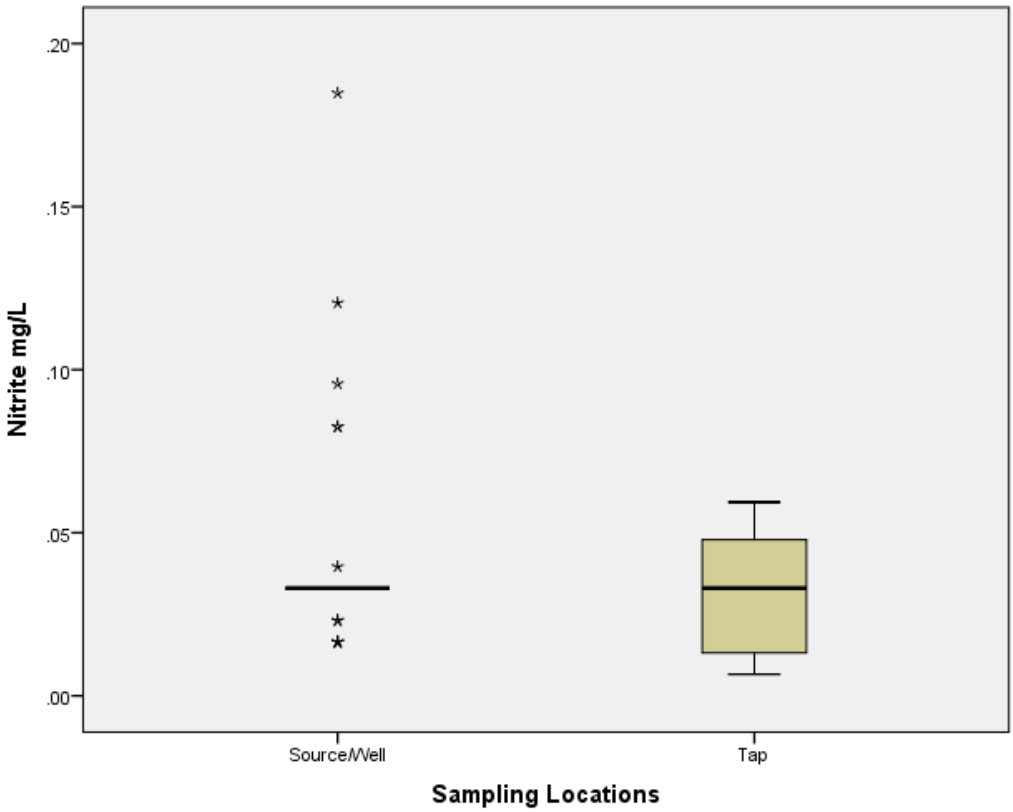


Figure 3.7: Boxplot showing nitrite concentrations measured in source and tap water samples collected in Christchurch.

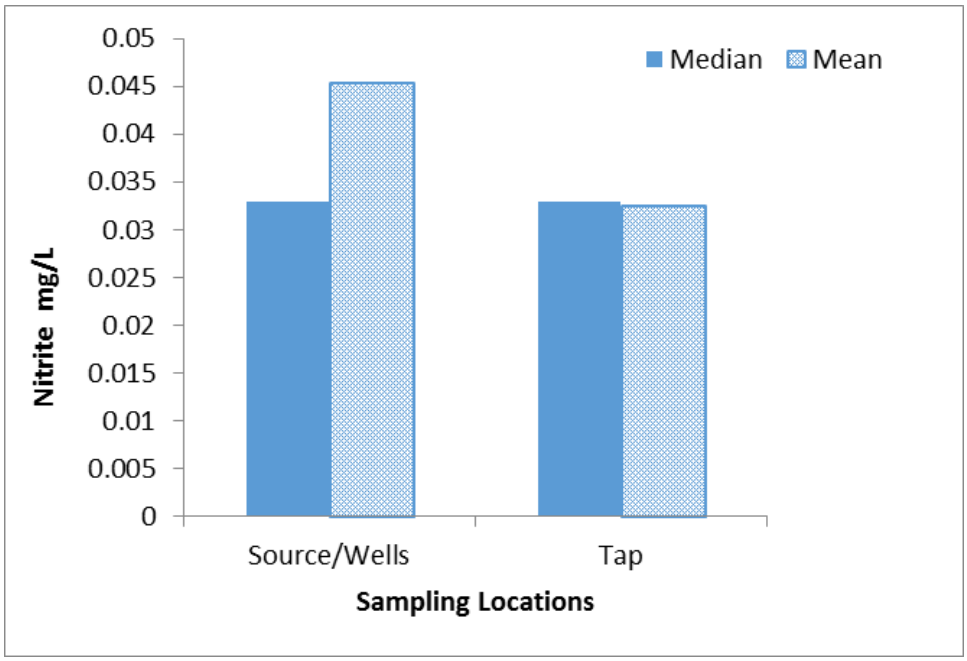


Figure 3.8: The median and mean nitrite concentrations determined in the source and tap water samples collected in Christchurch.

3.1.6. Total Zinc (Zn)

Table 3.2 summarises of the chemical parameter results measured in both source and tap water samples. The total zinc concentration varied from 0.001-0.086 mg/L in the source water. The concentrations measured in the household tap water samples varied from 0.002-0.200 mg/L. The results show that the tap water samples had greater maximum, minimum, median and mean zinc concentrations than those measured in the source water (Table 3.2 and Figure 3.9).

Figure 3.10 compares the mean and median values of total zinc concentrations measured in the source and tap water samples. A proportional amount of variation was found between the mean and median zinc concentrations measured in both the source and tap water samples. The tap water samples appear to have higher zinc concentrations. However, the independent samples t-test results indicate that the differences was not significantly different (*p=0.093*) (Table 3.3).

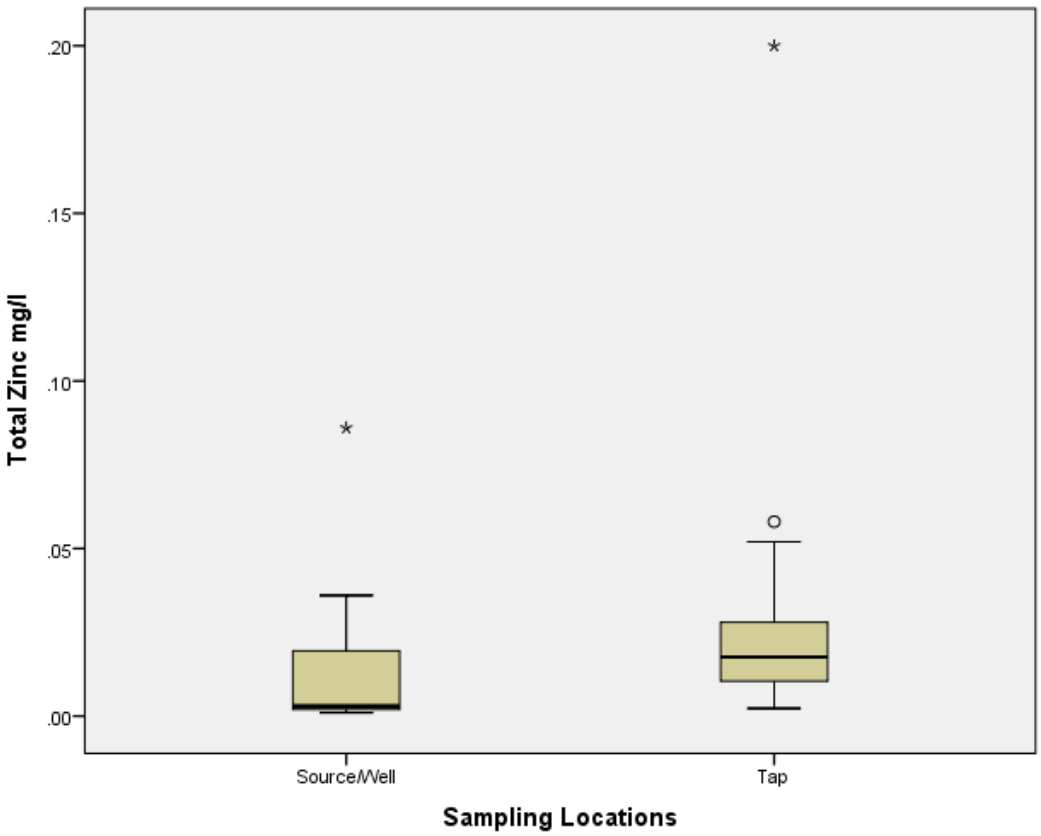


Figure 3.9: Boxplot showing total zinc concentrations measured in source and tap water samples in Christchurch.

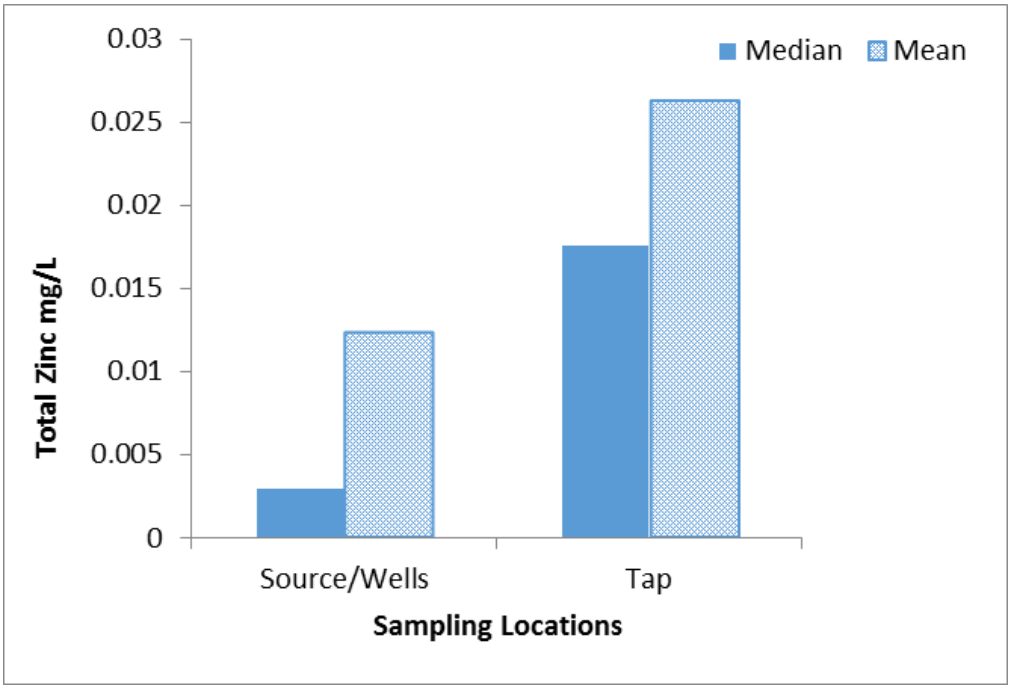


Figure 3.10: The median and mean total zinc concentrations determined in source and tap water samples collected in Christchurch.

3.1.7. Total Iron (Fe)

The descriptive statistics summary in Table 3.2 details the variation in total iron concentrations measured in the source and household tap water samples. The total iron concentration varied from 0.002-1.340 mg/L in the source water. The concentrations measured in the household tap water samples varied from 0.02-0.05 mg/L.

The distribution of concentrations measured in the tap water samples were very close to the mean and median values (Table 3.2 and Figure 3.11). The concentrations measured in the source water were found to be varied and outlier results were obtained. These outliers increase the mean concentration measured in the source waters (Figure 3.12). As a result, an elevated mean iron concentration was found in the source water even though an elevated iron concentration had been expected in the tap water. The independent samples t-test (Table 3.3) shows that the difference in iron concentrations were significantly different ($p=0.049$).

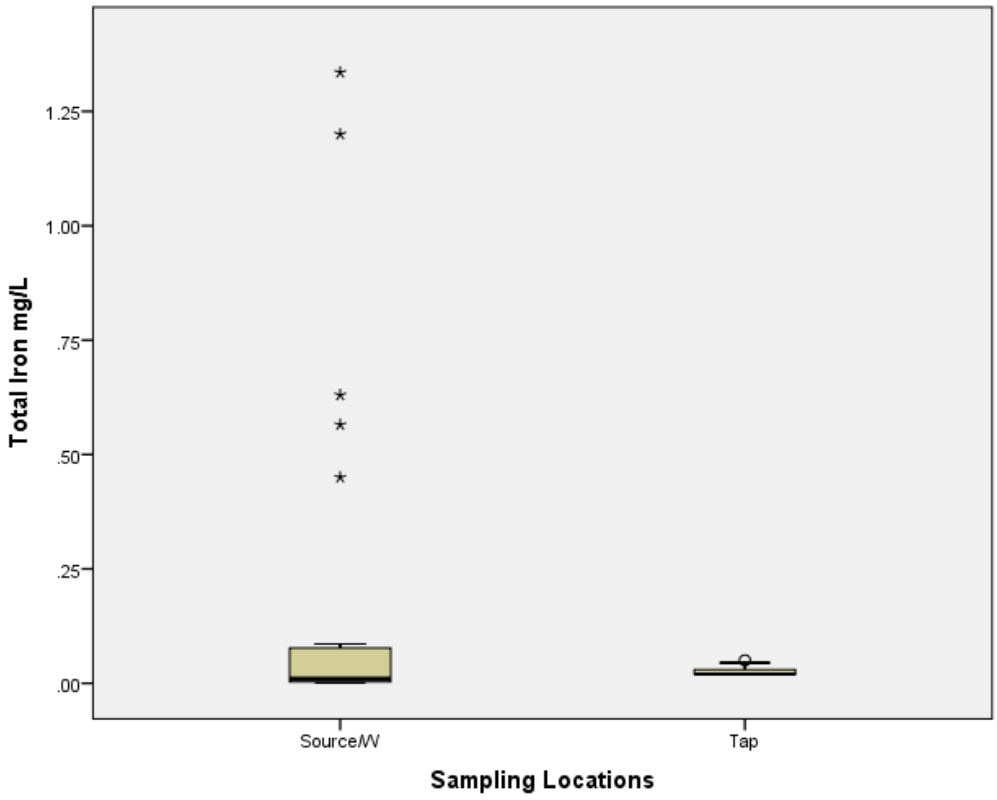


Figure 3.11: Boxplot showing total iron concentrations measured in source and tap water samples collected in Christchurch.

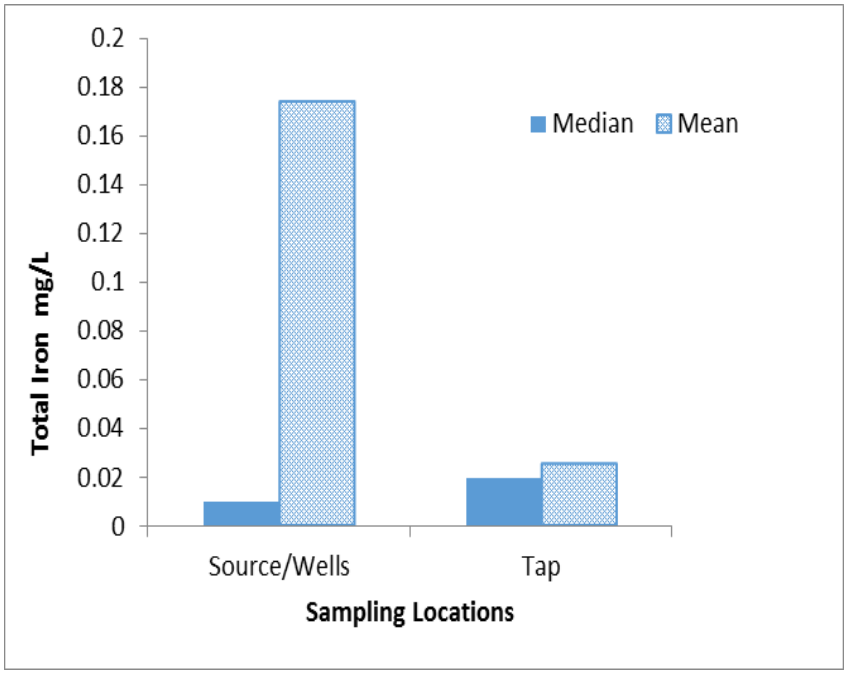


Figure 3.12: The median and mean total iron concentrations determined in source and tap water samples collected in Christchurch.

Table 3.2: Summary of water quality results for chemical parameters measured in source and tap water samples collected in Christchurch, New Zealand.

Parameters	Descriptive Statistic	Sampling location and No. of samples	
		Source (N=26)	Tap (N=27)
Nitrate (mg/l)	Maximum	28.73	11.93
	Minimum	0.27	1.99
	Median	1.33	5.75
	Mean	3.66	5.81
	Std Dev	5.79	2.07
Nitrite (mg/l)	Maximum	0.185	0.059
	Minimum	0.017	0.007
	Median	0.033	0.033
	Mean	0.045	0.033
	Std Dev	0.04	0.02
Total Zinc mg/l	Maximum	0.086	0.200
	Minimum	0.001	0.002
	Median	0.003	0.018
	Mean	0.012	0.026
	Std Dev	0.02	0.04
Total Iron (mg/l)	Maximum	1.340	0.050
	Minimum	0.002	0.020
	Median	0.010	0.020
	Mean	0.174	0.025
	Std Dev	0.37	0.01

3.1.8. *E. coli* and Faecal Coliform Bacteria

No *E. coli* and faecal coliform bacteria were found in either the source or tap water samples collected in Christchurch during this study. The absence of either E. coli or faecal coliform bacteria is good evidence of a quality water supply and good infrastructure. Christchurch City's drinking water supply is reputed to be among the best in the world.

Table 3.3: The independent samples t-test summary of results. Comparison of the mean pH, electrical conductivity, turbidity, nitrate, nitrite, total zinc and total iron values measured in samples collected in Christchurch, New Zealand. Parameters highlighted in grey are significant at the 5% level.

Group	Parameters	N=26 for Source/Well, N=27 for Tap		
		Compared locations	p-value	Significantly different?
Physical	pH	Source vs Tap	0.042	Yes
	Conductivity	Source vs Tap	0.554	No
	Turbidity	Source vs Tap	0.110	No
Chemical	Nitrate	Source vs Tap	0.083	No
	Nitrite	Source vs Tap	0.123	No
	Total Zinc	Source vs Tap	0.093	No
	Total Iron	Source vs Tap	0.049	Yes
Biological	*E. coli*	Source vs Tap	N.A	N.A
	Faecal Coliform	Source vs Tap	N.A	N.A

***N/A: The independent samples t-test was not performed as no E. coli and faecal coliform bacteria were detected in any sample.*

3.2. Household Drinking Water in Addis Ababa Addis Ababa

In order to determine if the water supply infrastructure is affecting water quality in Addis Ababa, water was collected for analysis from the Legedadi Treatment Plant (LTP) and households of the Bole subcity. A comparative study was conducted between the Woreda-8 and Woreda-6 districts.

The independent samples t-test was used to compare the means of water quality results measured in samples collected from the LTP, Woreda-8 (W-8), Woreda-6 (W-6) and the wider Bole subcity (B.S). Pairwise comparative analysis was conducted between the: LTP and W-8; LTP and W-6; LTP and the wider Bole subcity (B.S); and W-8 and W-6. A summary of water quality results and those obtained from the independent samples t-test are summarised in Table 3.4, Table 3.5 Table 3.6, Table 3.7, Table 3.8 and Table 3.9. The variations in water quality measured between the treatment plant and household taps are presented in this sub-chapter.

3.2.1. pH

Table 3.4 summarises the descriptive statistics calculated for the pH levels measured in all study areas. The highest pH levels measured from the LTP, W-8, W-6 and the wider Bole

subcity (B.S) were 7.36, 7.36, 7.42 and 7.46, respectively. The lowest pH levels measured from the LTP, W-8, W-6 and the B.S were 6.60, 6.46, 6.46 and 6.46, respectively. A similar range of pH levels were measured among the study areas.

Figure 3.13 shows the variation of pH levels measured from the LTP, W-8, W-6 and the wider Bole subcity (B.S). The median values indicate that the pH levels varied between the LTP and the household taps. In general, a decrease in pH level was observed after treated water left the treatment plant and entered into the distribution system. The lowest median pH values were measured in the household tap water samples collected far away from the LTP.

The median pH values calculated for samples collected from the LTP, W-8, W-6 and the wider Bole subcity (B.S) were varied. Similar median pH values were determined for the LTP and W-8 samples. The lowest median pH value was determined in tap water samples collected from W-6. The highest median pH value was determined in the tap water samples collected from the wider Bole subcity (B.S) (Table 3.4 and Figure 3.13).

Pairwise comparison of mean pH values were conducted using the independent samples t-test (Table 3.5). The results indicate that the mean pH values compared between the LTP and W-8, LTP and W-6, LTP and the wider Bole subcity (B.S), and W-8 and W-6 were not significantly different ($p = 0.798$, 0.638, 0.668 and 0.683, respectively).

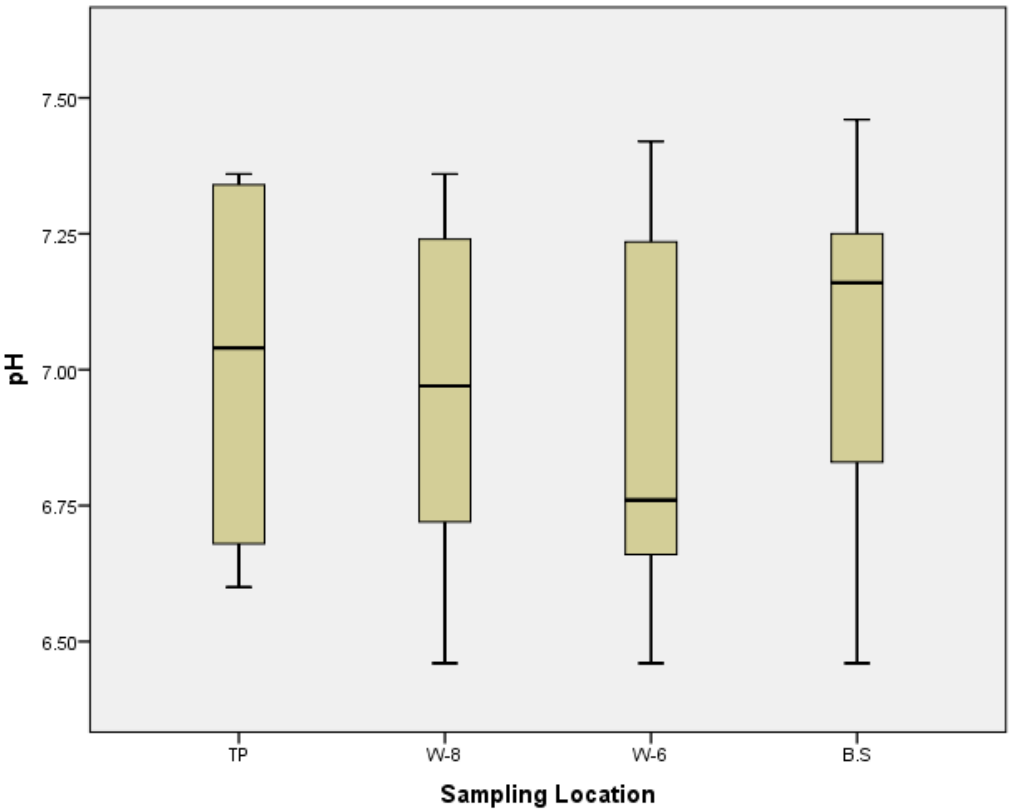


Figure 3.13: Boxplot showing pH levels measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

3.2.2. Conductivity

Table 3.4 summarises the descriptive statistics calculated for conductivity measurements obtained at all study areas. The conductivity of the samples from the LTP, W-8, W-6 and wider Bole subcity (B.S) ranged from 100.5-110.6, 101.2- 147.5, 115.4-165.5, and 106.4-178.3 µS/cm, respectively. The highest mean and median values were measured in the tap water samples collected from W-6. The highest conductivity values of 165.5 and 178.3 µS/cm were also measured in tap water samples collected from W-6 and the wider Bole subcity (B.S), respectively.

The results indicate that conductivity values were higher in samples collected from household taps. The highest conductivity results were measured in samples collected from household taps in remote locations (Table 3.4). Figure 3.14 shows the variation in conductivity values amongst the sampling locations. The median conductivity values are higher in samples collected from W-8 and W-6. The median conductivity value for the wider Bole subcity (B.S) was lower than

that determined in W-6. In general, the conductivity of the water increases as the treated water leaves the LTP and enters into the distribution system (Figure 3.14).

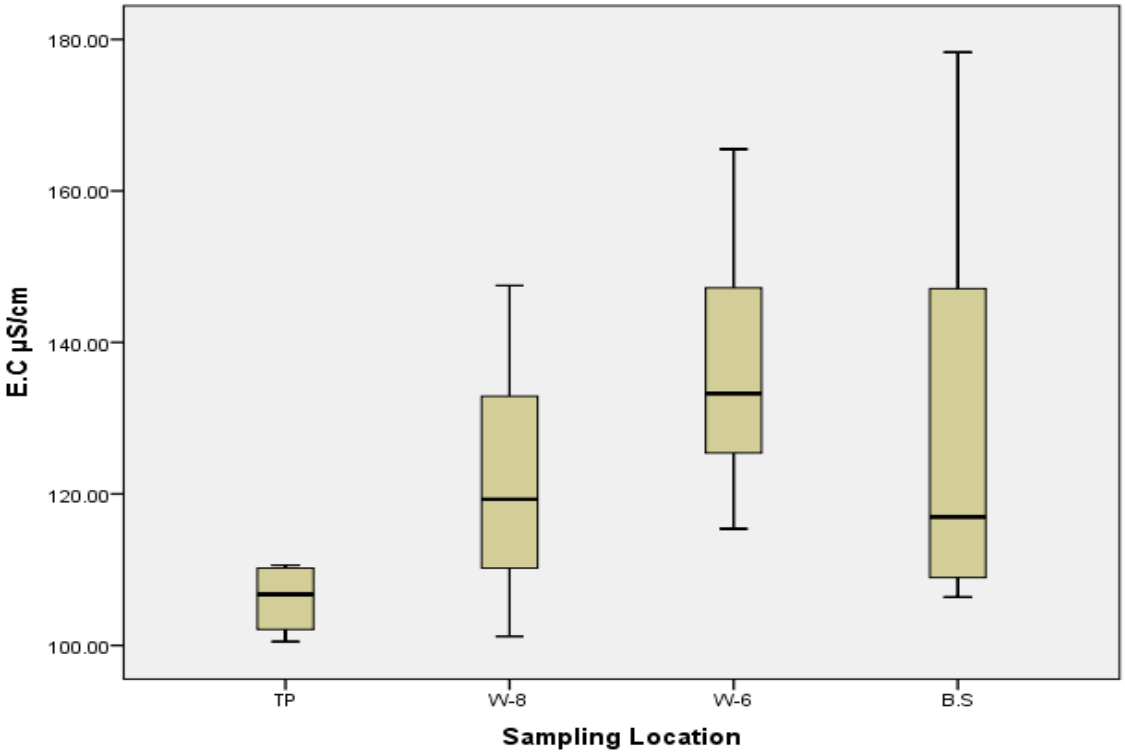


Figure 3.14: Boxplot showing electrical conductivity values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to determine the mean conductivity measurements compared between the LTP and W-8, LTP and W-6, LTP and the wider Bole subcity (B.S), and W-8 and W-6. The conductivity difference for all paired locations was found to be statistically significant (*p=0.001*) (Table 3.5).

3.2.3. Turbidity

The turbidity values measured in samples collected from the LTP, W-8, W-6, and wider Bole subcity (B.S) ranged from 0.43-2.50, 0.55-2.01, 0.78-9.30 and 0.55-7.20 NTU, respectively. Table 3.4 summarises the turbidity data. The greatest turbidity values of 9.30 and 7.20 NTU were measured in tap water samples collected from W-6 and the wider Bole subcity (B.S), respectively. The maximum turbidity measured in samples collected from the LTP was 2.50

NTU. In general, there were no large variations in the median turbidity values measured in samples from all locations (Figure 3.15).

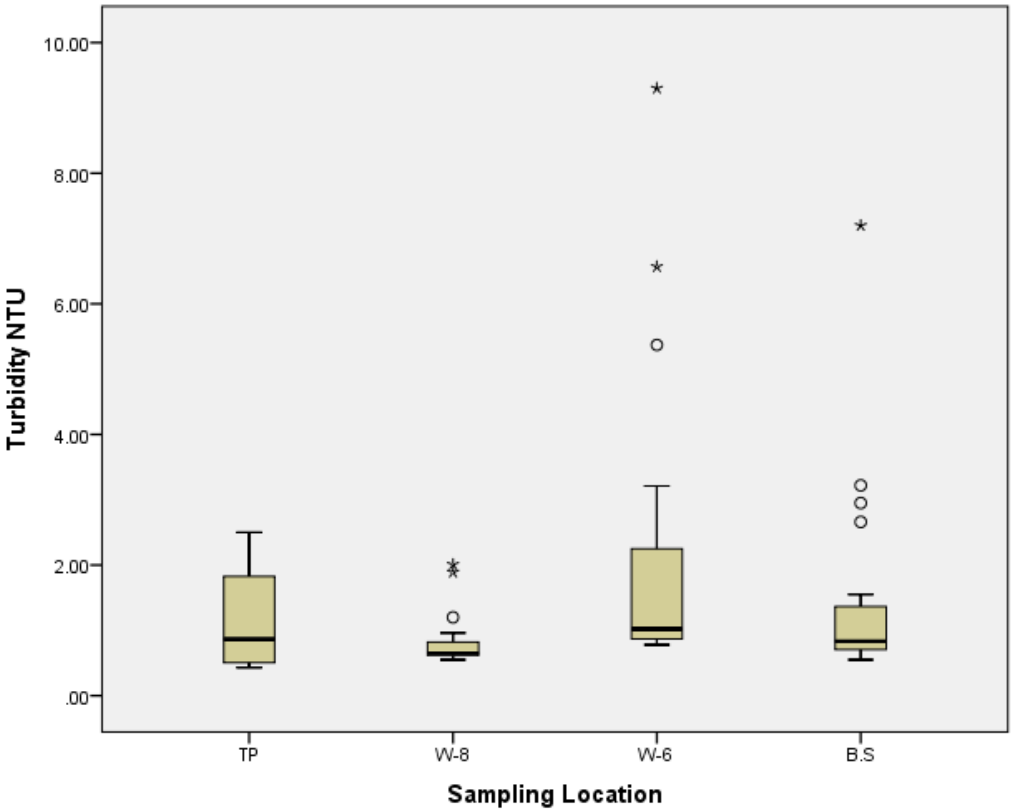


Figure 3.15: Boxplot showing turbidity values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the mean turbidity results. No significant differences were found in turbidity means compared between the LTP and W-8 and the LTP and W-6 ($p=0.540$ and 0.432, respectively) (Table 3.5).

The turbidity values measured in samples collected from W-8 and W-6 were compared. 65% of the samples collected from W-6 had turbidity values >1 NTU. 85% of the samples collected from W-8 had turbidity values <1 NTU. The independent samples t-test determined that turbidity values in W-8 and W-6 were significantly different ($p=0.024$) (Table 3.5).

Table 3.4: Summary of water quality results for physical parameters measured in source and tap water samples collected in Addis Ababa, Ethiopia.

Parameters	Descriptive Statistic	Sampling locations and No. of samples			
		LTP (N=4)	W-8 (N=20)	W-6 (N=20)	Wider B.S (N=20)
pH	Maximum	7.36	7.36	7.42	7.46
	Minimum	6.60	6.46	6.46	6.46
	Median	7.04	6.97	6.76	7.16
	Mean	7.01	6.97	6.93	7.08
	Std Dev	0.39	0.29	0.30	0.28
Conductivity (µS/cm)	Maximum	110.6	147.5	165.5	178.3
	Minimum	100.5	101.2	115.4	106.4
	Median	106.75	119.30	133.25	116.95
	Mean	106.15	121.26	136.70	128.91
	Std Dev	4.87	12.98	14.85	23.24
Turbidity (NTU)	Maximum	2.50	2.01	9.30	7.20
	Minimum	0.43	0.55	0.78	0.55
	Median	0.87	0.65	1.02	0.84
	Mean	1.17	0.84	2.13	1.48
	Std Dev	0.94	0.41	2.33	1.57

Table 3.5: The independent samples t-test summary of results. Comparison of the mean pH, conductivity and turbidity values measured in samples collected in Addis Ababa, Ethiopia. Parameters highlighted in grey are significant at the 5% level.

Group	Parameters	N=4 for LTP, N=20 for W-8, W-6 and wider B.S		
		Compared locations	p-value	Significantly different?
Physical	pH	LTP and W-8	0.798	No
		LTP and W-6	0.638	No
		LTP and B.S	0.666	No
		W-8 and W-6	0.683	No
	Conductivity	LTP and W-8	0.001	Yes
		LTP and W-6	0.001	Yes
		LTP and B.S	0.001	Yes
		W-8 and W-6	0.001	Yes
	Turbidity	LTP and W-8	0.540	No
		LTP and W-6	0.432	No
		LTP and B.S	0.708	No
		W-8 and W-6	0.024	Yes

3.2.4. Nitrate (NO_3)

The nitrate concentrations measured in samples collected from the LTP, W-8, W-6 and the wider Bole subcity (B.S) do not appear to vary consistently (Figure 3.16) The minimum, median and mean concentrations were nearly similar at all sites (Table 3.6).

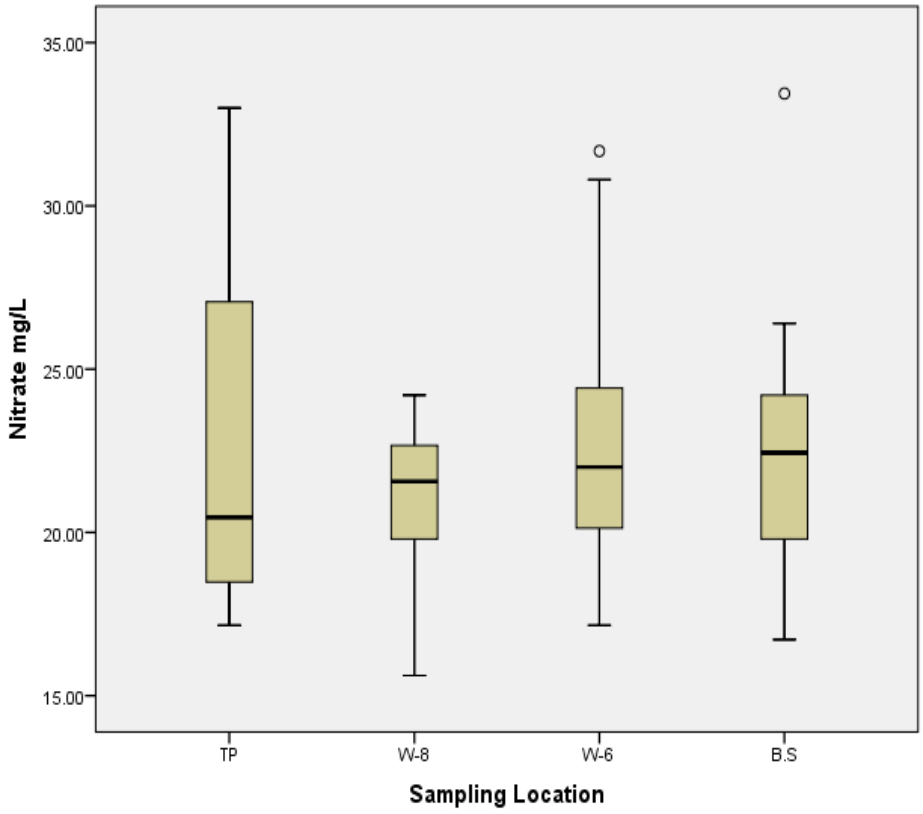


Figure 3.16: Boxplot showing nitrate concentration values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the mean nitrate concentrations (Table 3.7). The nitrate concentrations compared between the LTP and W-8, LTP and W-6, LTP and the wider Bole subcity (B.S), and W-8 and W-6 were not significantly different ($p=0.635$, *0.997*, *0.889* and *0.103*, respectively).

3.2.5. Nitrite (NO_2)

The nitrite concentrations measured in the source water collected from the LTP varied from 0.016-0.024 mg/L. The median and mean concentrations were similar. The nitrite

concentrations measured in tap water samples collected from W-8, W-6 and the wider Bole subcity (B.S) ranged from 0.010-0.040, 0.007-0.026 and 0.009-0.022 mg/L, respectively (Table 3.6).

As shown in Figure 3.17 and Table 3.6, nitrite concentrations measured in samples collected from household taps in W-6 and W-8 were generally lower than those measured at the LTP. The nitrite concentrations in samples collected from the wider Bole subcity (B.S) were generally higher than W-8 and W-6 (Figure 3.17).

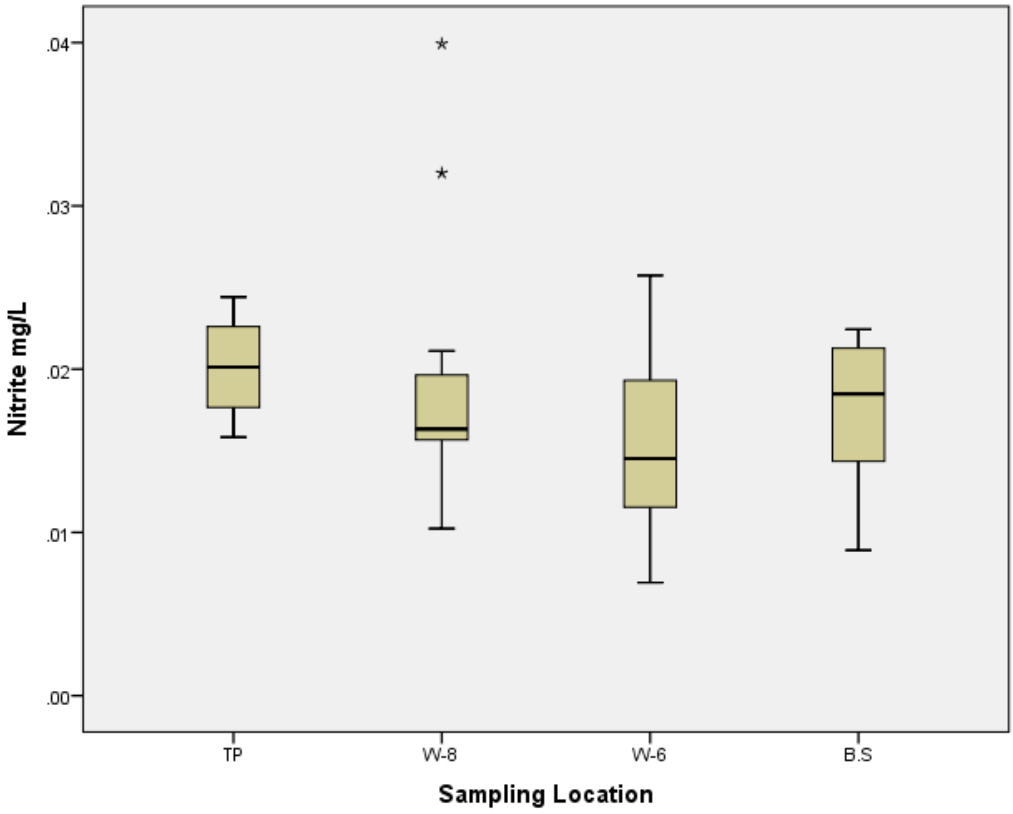


Figure 3.17: Boxplot showing nitrite concentration values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the mean nitrite concentrations (Table 3.7). The nitrite concentrations compared between the LTP and W-8, LTP and W-6, LTP and wider Bole subcity (B.S), and W-8 and W-6 were not significantly different (*p=0.665*, *0.116*, *0.249* and *0.089*, respectively).

3.2.6. Total Zinc (Zn)

The range, median and mean zinc concentrations measured at all sampling locations are summarised in Table 3.6. The results show that zinc concentrations varied from 1.11-1.26, 1.18-1.58, 1.21-1.49 and 1.19-1.47 mg/L in the samples collected from the LTP, W-8, W-6 and the wider Bole subcity (B.S), respectively.

The mean and median zinc concentrations measured in household tap samples were very similar. All were higher than those calculated from the LTP source. An increase in zinc concentrations occurs as the treated water leaves the LTP and passes through the water supply distribution system. A single water sample collected from a household in W-8 had the highest reported zinc concentration. This sample also had elevated turbidity and nitrite values (Table 3.6 and Figure 3.15).

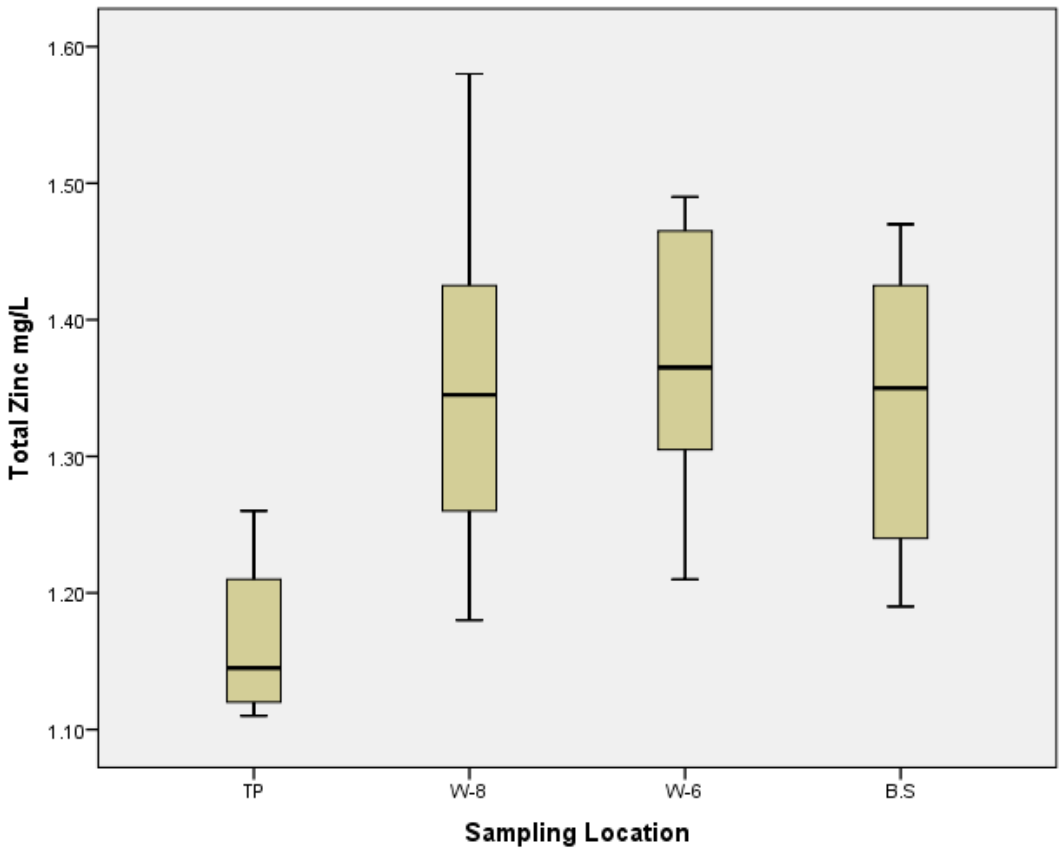


Figure 3.18: Boxplot showing total zinc concentration values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the mean total zinc concentrations (Table 3.7). The total zinc concentrations compared between the LTP and W-8, LTP and W-6, and LTP and the wider Bole subcity (B.S) were significantly different (*p=0.005*, *<0.001* and *0.002*, respectively). The mean concentrations between W-8 and W-6 were not significantly different (*p=0.387*).

3.2.7. Total Iron (Fe)

The range, median and mean iron concentrations measured at all sampling locations are summarised in Table 3.6. The total iron concentrations measured in samples collected from the LTP ranged from 0.023-0.039 mg/L. The concentrations measured in samples collected from W-8, W-6, and the wider Bole subcity (B.S) varied from 0.006-0.735, 0.028-0.538, and 0.012-0.252 mg/L, respectively.

The total iron concentrations measured in samples collected from the LTP source and household taps were very different. In general, the concentration of total iron increased in the household tap water samples (Table 3.6 and Figure 3.19). The highest concentration was measured in a single tap water sample collected in W-8. The remaining outliers measured in W-6 and the wider Bole subcity (B.S) were measured in samples collected after supply interruption and reinstatement events.

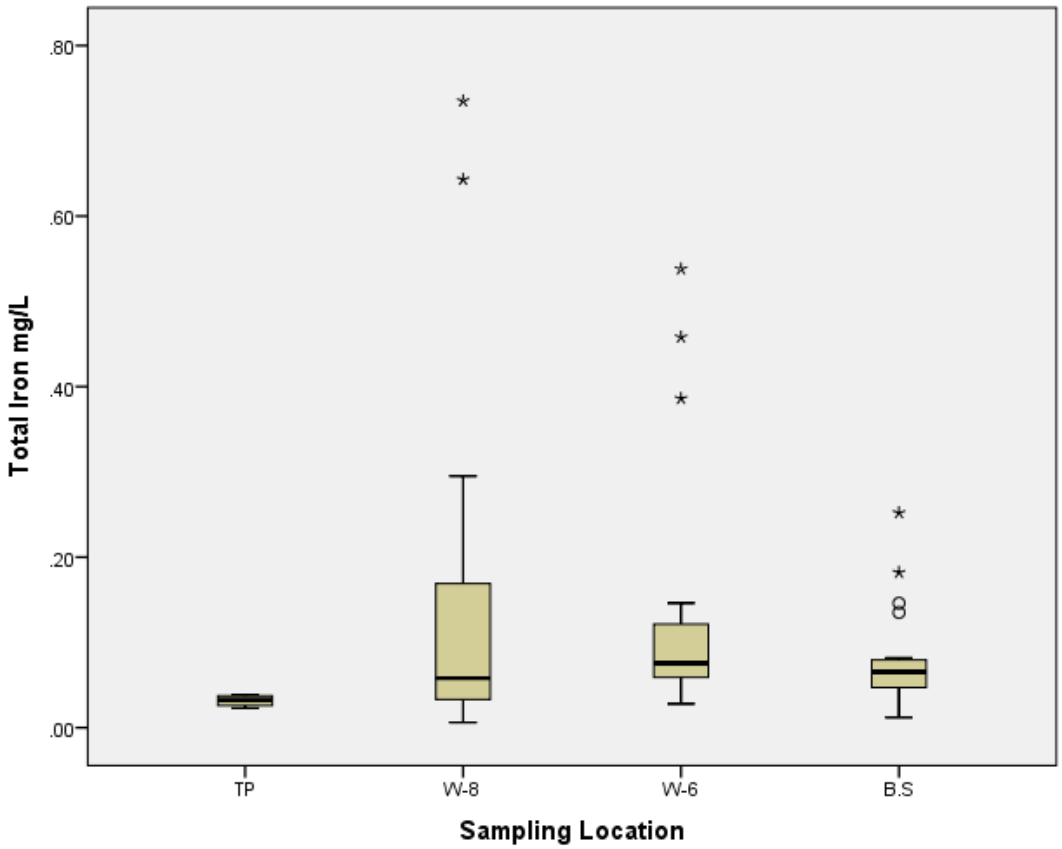


Figure 3.19: Boxplot showing total iron concentration values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the mean total iron concentrations (Table 3.7). The total iron concentrations compared between the LTP and W-6, and LTP and the wider Bole subcity (B.S) were significantly different (*p=0.006* and *0.002*, respectively). The total iron concentrations between LTP and W-8, and W-8 and W-6 were not significantly different (*p=0.288* and *0.870*, respectively).

3.2.8. Residual Chlorine

The range, median and mean residual chlorine concentrations measured at all sampling locations are summarised in Table 3.6. All residual chlorine samples were found to have very similar concentrations to the mean value of 0.83 ± 0.05 mg/L. However, the mean residual chlorine levels measured in water samples collected from W-8, W-6 and the wider Bole subcity (B.S) were 0.47 ± 0.08, 0.12 ± 0.11, and 0.16 ± 0.17 mg/L, respectively.

The residual chlorine concentrations measured in samples from the LTP, W-8, W-6 and the wider Bole subcity (B.S) were highly variable (Figure 3.20). The highest residual chlorine concentrations were measured at the LTP. The lowest concentrations were measured in household tap water samples collected in W-8, W-6 and the wider Bole subcity (B.S).

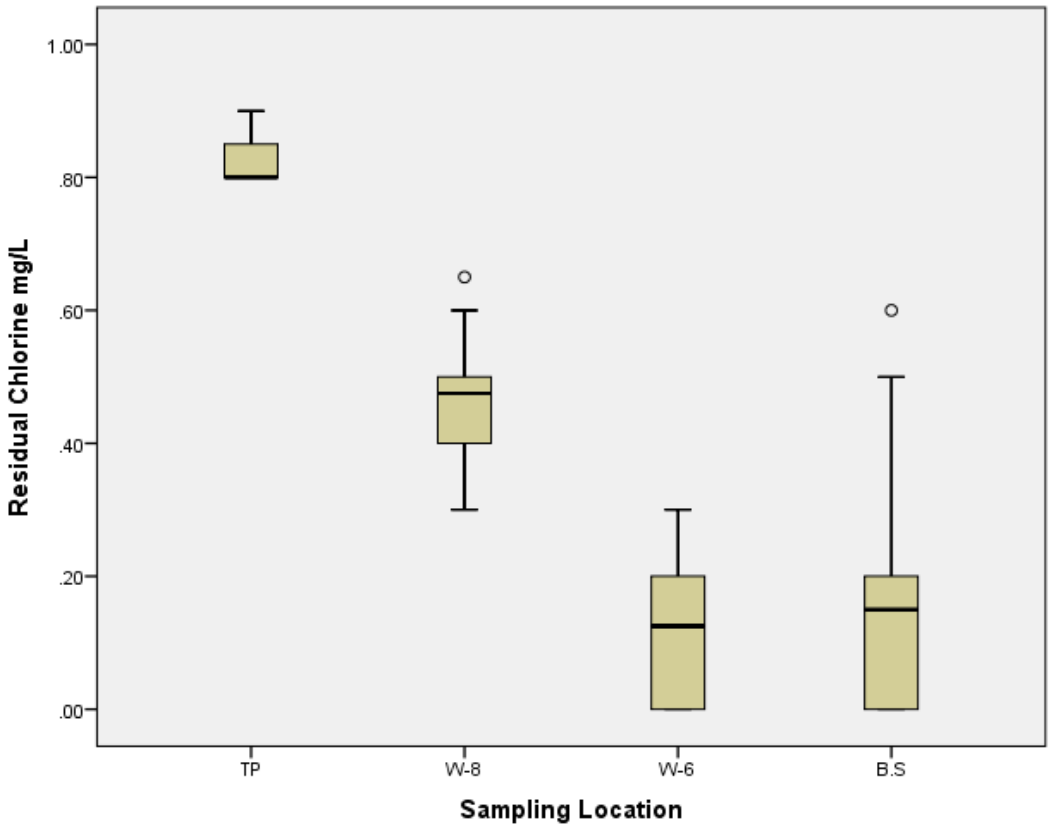


Figure 3.20: Boxplot showing residual chlorine concentration values measured in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the mean residual chlorine concentrations (Table 3.7). The residual chlorine concentrations compared between the LTP and W-8, LTP and W-6, LTP and the wider Bole subcity (B.S), and W-8 and W-6 were found to be significantly different ($p < 0.001$).

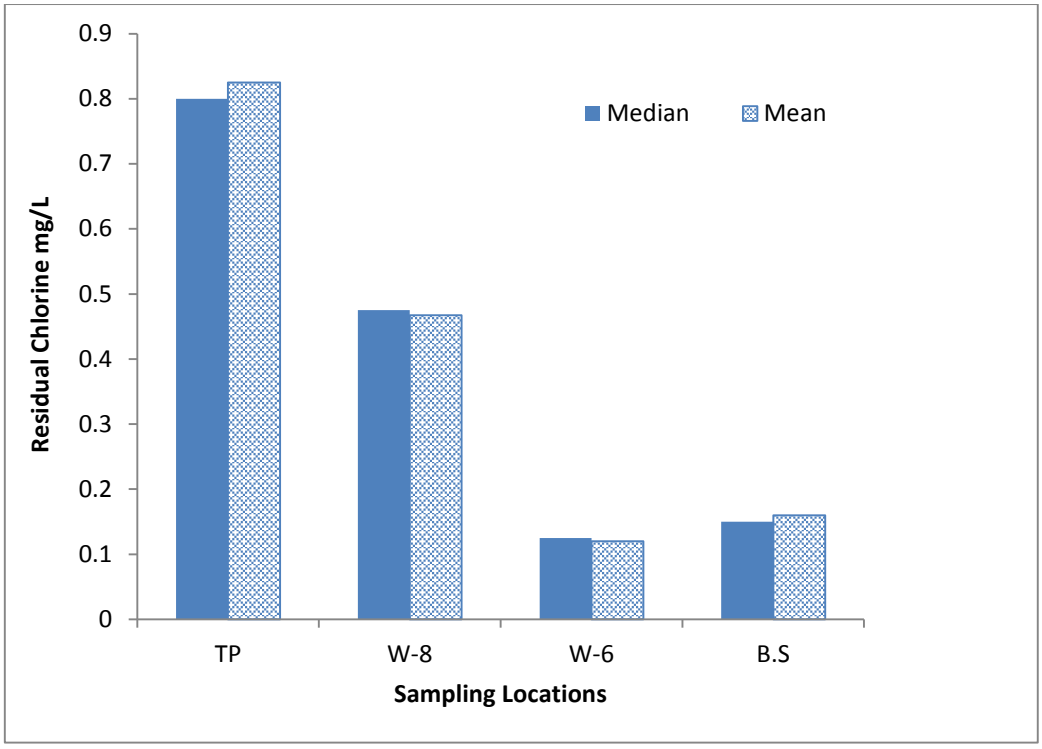


Figure 3.21: Mean and median residual chlorine concentrations determined in water samples collected from LTP, W-8, W-6 and wider B.S.

The mean and median residual chlorine concentrations are shown in Figure 3.21. The median values of residual chlorines measured from LTP, W-8, W-6 and the wider Bole subcity (B.S) were 0.80, 0.48, 0.13 and 0.15 mg/L, respectively (Table 3.6). The median and mean values of residual chlorines within all sites were similar (Table 3.6). The residual chlorine concentrations are lower in the household tap water samples. Tap water samples collected from households in W-6 and the wider Bole subcity (B.S) had very low concentrations of residual chlorine.

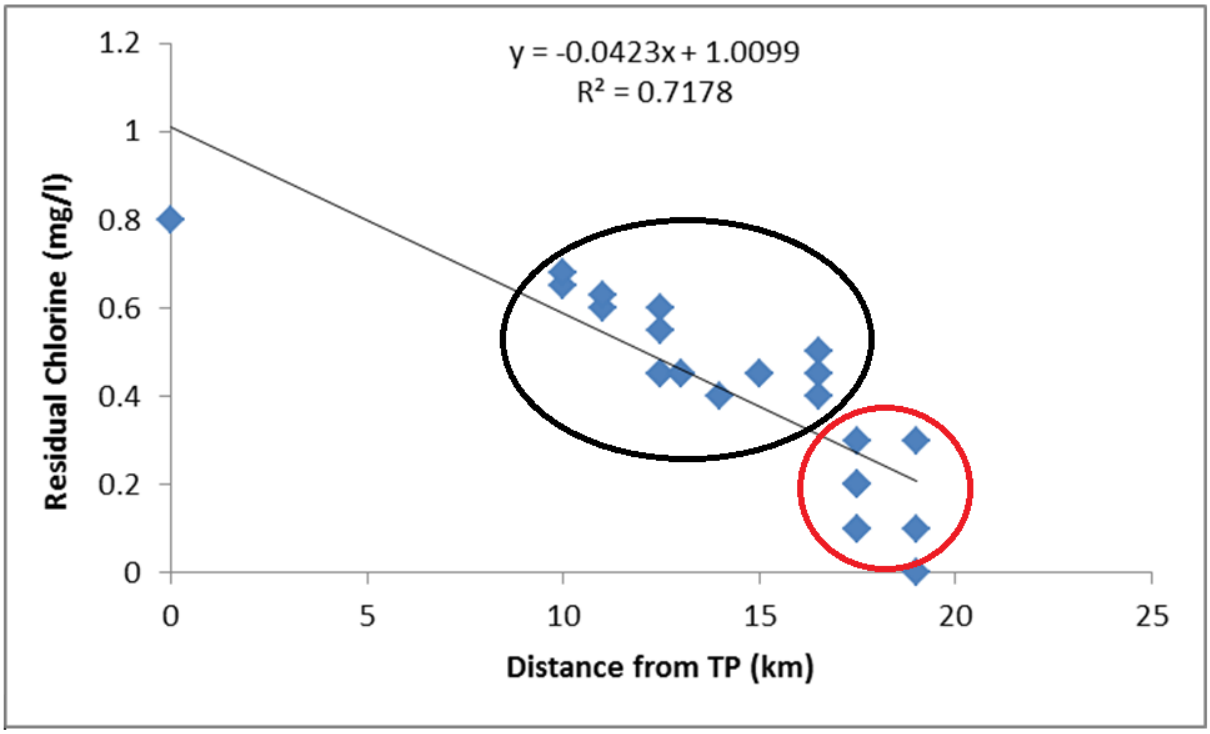


Figure 3.22: Scatter graph plotting the residual chlorine concentrations against the distance away from the LTP where samples were collected. Note: The distance between the LTP and households was measured using maps in geodistance (geodistance.com). The measurements are not indicative of the length of the water supply pipelines.

The scattered plot of distance from LTP versus residual chlorine in Figure 3.22 shows an inverse relationship between the households' distance from LTP and reduction in residual chlorine concentrations. The data points inside the black circle indicate households (W-8) close to the LTP. The data points in the red circle indicate houses (W-6 and the wider Bole subcity) far away from the LTP. The concentration of residual chlorine tends to decrease when the households' distance gets far from LTP. The lowest residual chlorine concentrations were found in tap water samples collected from the most remote households in W-6 and the wider Bole subcity (B.S).

Table 3.6: Summary of water quality results for chemical parameters measured in source and tap water samples collected in Addis Ababa, Ethiopia.

Parameters	Descriptive statistics	Sampling locations and No. of samples			
		LTP (N=4)	W-8 (N=20)	W-6 (N=20)	Wider B.S (N=20)
Nitrate (mg/l)	Maximum	33.00	24.20	31.68	33.44
	Minimum	17.16	15.62	17.16	16.72
	Median	20.46	21.56	22.00	22.44
	Mean	22.77	20.91	22.78	22.44
	Std Dev	7.02	2.51	4.32	3.66
Nitrite (mg/l)	Maximum	0.024	0.04	0.026	0.022
	Minimum	0.016	0.010	0.007	0.009
	Median	0.02	0.02	0.01	0.02
	Mean	0.02	0.02	0.02	0.02
	Std Dev	0.00	0.01	0.01	0.00
Total Zinc mg/l	Maximum	1.26	1.58	1.49	1.47
	Minimum	1.11	1.18	1.21	1.19
	Median	1.15	1.35	1.37	1.35
	Mean	1.17	1.34	1.37	1.34
	Std Dev	0.07	0.11	0.09	0.09
Total Iron (mg/l)	Maximum	0.039	0.735	0.538	0.252
	Minimum	0.023	0.006	0.028	0.012
	Median	0.03	0.06	0.08	0.07
	Mean	0.03	0.14	0.13	0.08
	Std Dev	0.01	0.20	0.15	0.06
Residual Chlorine (mg/l)	Maximum	0.90	0.65	0.30	0.60
	Minimum	0.8	0.3	0.0	0.0
	Median	0.80	0.48	0.13	0.15
	Mean	0.83	0.47	0.12	0.16
	Std Dev	0.05	0.08	0.11	0.17

Table 3.7: The independent samples t-test summary of results. Comparison of the mean nitrate, nitrite, total zinc, total iron and residual chlorine concentrations measured in samples collected in Addis Ababa, Ethiopia. Parameters highlighted in grey are significant at the 5% level.

Group	Parameters	N=4 for LTP, N=20 for W-8, W-6 and wider B.S		
		Compared locations	p-value	Significantly different?
Chemical	Nitrate	LTP and W-8	0.635	No
		LTP and W-6	0.997	No
		LTP and B.S	0.889	No
		W-8 and W-6	0.103	No
	Nitrite	LTP and W-8	0.665	No
		LTP and W-6	0.116	No
		LTP and B.S	0.249	No
		W-8 and W-6	0.089	No
	Total Zinc	LTP and W-8	0.005	Yes
		LTP and W-6	<0.001	Yes
		LTP and B.S	0.002	Yes
		W-8 and W-6	0.387	No
	Total Iron	LTP and W-8	0.288	No
		LTP and W-6	0.006	Yes
		LTP and B.S	0.002	Yes
		W-8 and W-6	0.870	No
	Residual Chlorine	LTP and W-8	<0.001	Yes
		LTP and W-6	<0.001	Yes
		LTP and B.S	<0.001	Yes
		W-8 and W-6	<0.001	Yes

3.2.9. *E. coli* and Total Coliform Bacteria

To determine if household drinking water was contaminated by faecal bacteria, the water samples collected from the LTP and household taps in W-8, W-6 and the wider Bole subcity (B.S) were analysed for concentrations of *E. coli* (Escherichia coli). As shown in Figure 3.23 and Table 3.8, no *E. coli* bacteria were found in water samples collected from the LTP. The median *E. coli* concentrations measured in the tap water samples from W-8, W-6 and the wider Bole subcity (B.S) were also 0 CFU/100ml. However, *E. coli* bacteria was found in 35% and 40% of water samples collected in W-6 and the wider Bole subcity (B.S), with concentrations ranging from 2-33 and 2-32 CFU/100ml, respectively. The majority of samples collected in W-8 were free of *E. coli*. Two samples had concentrations < 2 CFU/100ml.

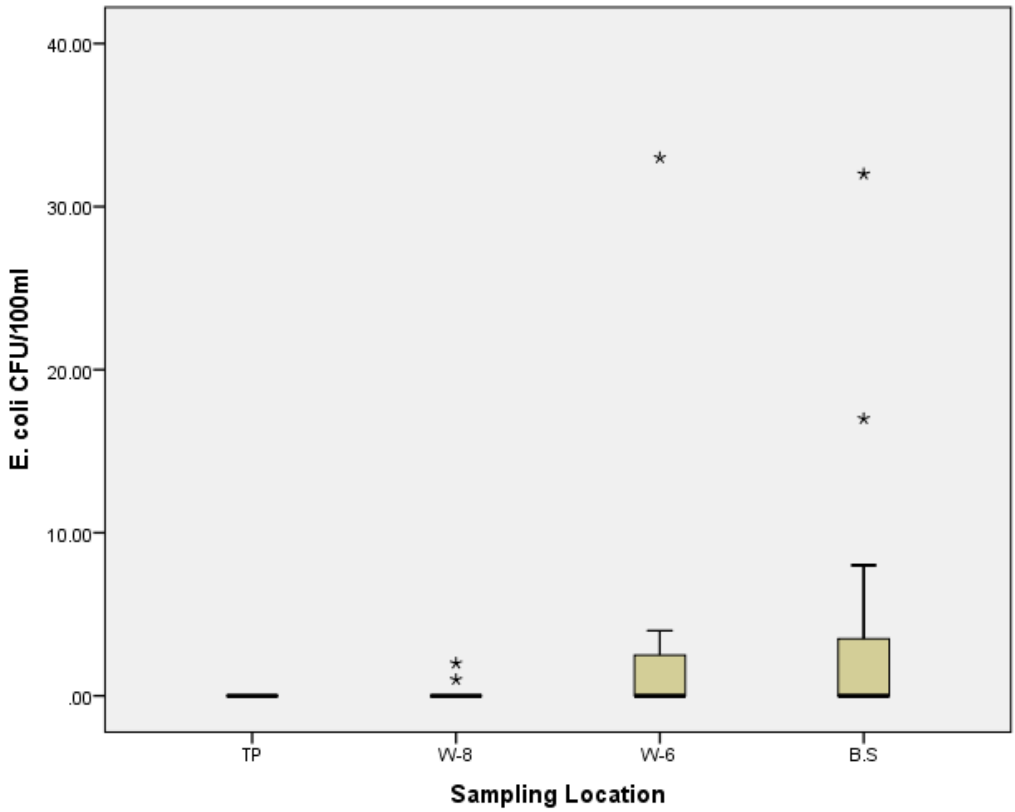


Figure 3.23: Boxplot showing *E. coli* concentration counts in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

The independent samples t-test was used to compare the *E. coli* concentrations (Table 3.9). The *E. coli* concentrations between the LTP and W-8, the LTP and W-6, the LTP and the wider Bole subcity (B.S), and W-8 and W-6 were not significantly different (*p= 0.553*, *0.501*, *0.360* and *0.151*, respectively).

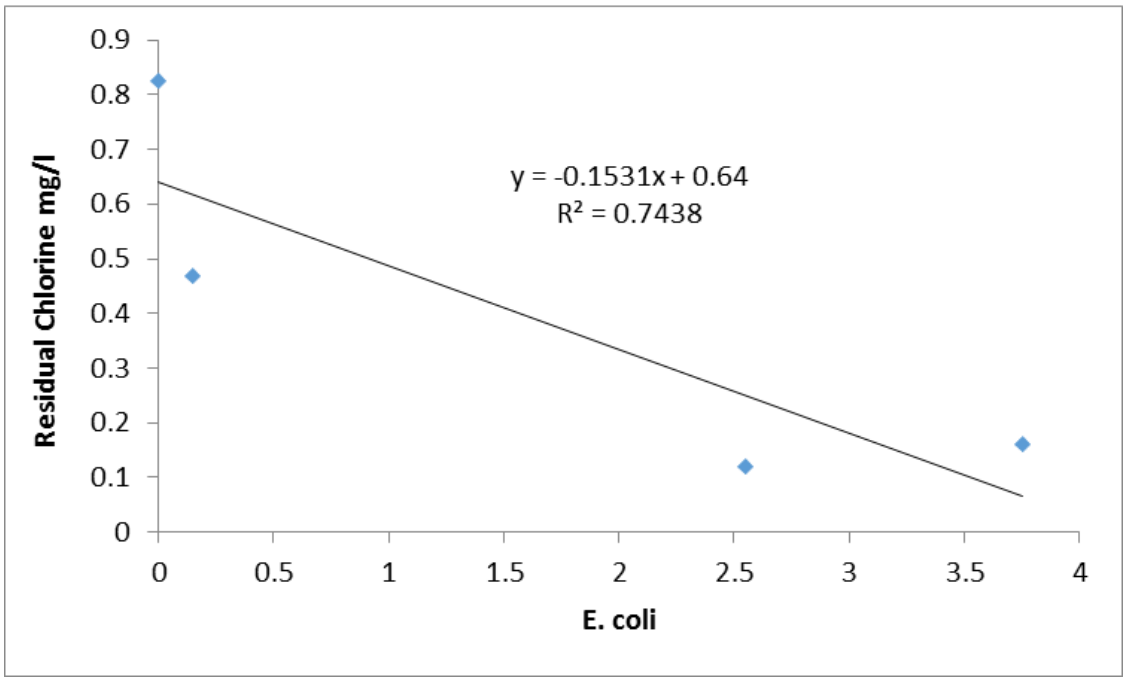


Figure 3.24: Scatter graph showing the correlation between the mean concentrations of residual chlorine and concentrations of *E. coli* in water samples collected from the LTP, W-8, W-6 and wider B.S.

The scattered plot of *E. coli* versus residual chlorine in Figure 3.24 shows an inverse relationship between the residual chlorine concentration and concentration of *E. coli* detected in samples. This implies that *E. coli* bacteria counts increased when the residual chlorine concentration decreased. The highest *E. coli* concentrations were found in tap water samples collected from the most remote households in W-6 and the wider Bole subcity (B.S). The residual chlorine in some of these households was as low as less than DL of the instrument.

Total coliform bacteria are relatively harmless and are commonly found in soil, in decayed vegetation and in surface waters. However, they also originate from sewage. The presence of total coliform bacteria in drinking water can be an indicator for the presence of other disease-causing pathogens. Water samples were analysed for total coliform bacteria in order to detect any general environmental contamination of the drinking water that may occur in the distribution infrastructure.

The summary of results for total coliform bacteria is presented in Table 3.8. No total coliform bacteria were found in the treated water leaving the LTP. However, concentrations of up to 144 and 71 CFU/100ml total coliform bacteria were found in tap water samples collected from W-

6 and the wider Bole subcity (B.S), respectively. Compared to W-6 and the wider Bole subcity (B.S), lower concentrations up to 40 CFU/100ml of total coliform bacteria were detected in W-8.

The median concentrations of total coliform bacteria detected in W-8 and W-6 were 0 CFU/100ml. The median concentration for the wider Bole subcity (B.S) was >4 CFU/100ml (Figure 3.25). However, total coliform bacteria concentrations ranging from 4-40, 4-144, and 1-71 CFU/100ml were found in 20%, 45% and 60% of the water samples collected from W-8, W-6 and the wider Bole subcity (B.S), respectively. The independent samples t-test was used to compare the total coliform concentrations (Table 3.9). The total coliform concentrations between the LTP and W-8, the LTP and W-6, the LTP and the wider Bole subcity (B.S), and W-8 and W-6 were not significantly different ($p=0.450$, 0.499, 0.237, and 0.363, respectively).

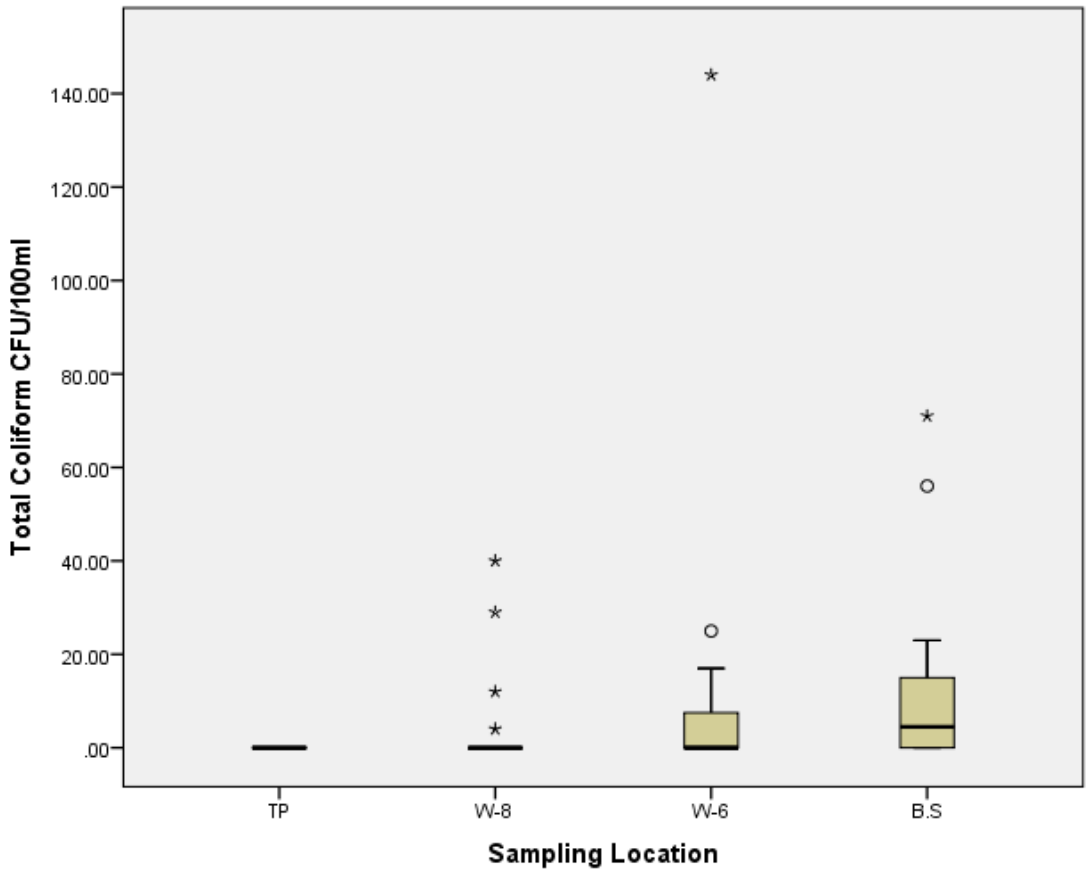


Figure 3.25: Boxplot showing total coliform concentration counts in water samples collected from the LTP, W-8, W-6 and wider B.S in Addis Ababa.

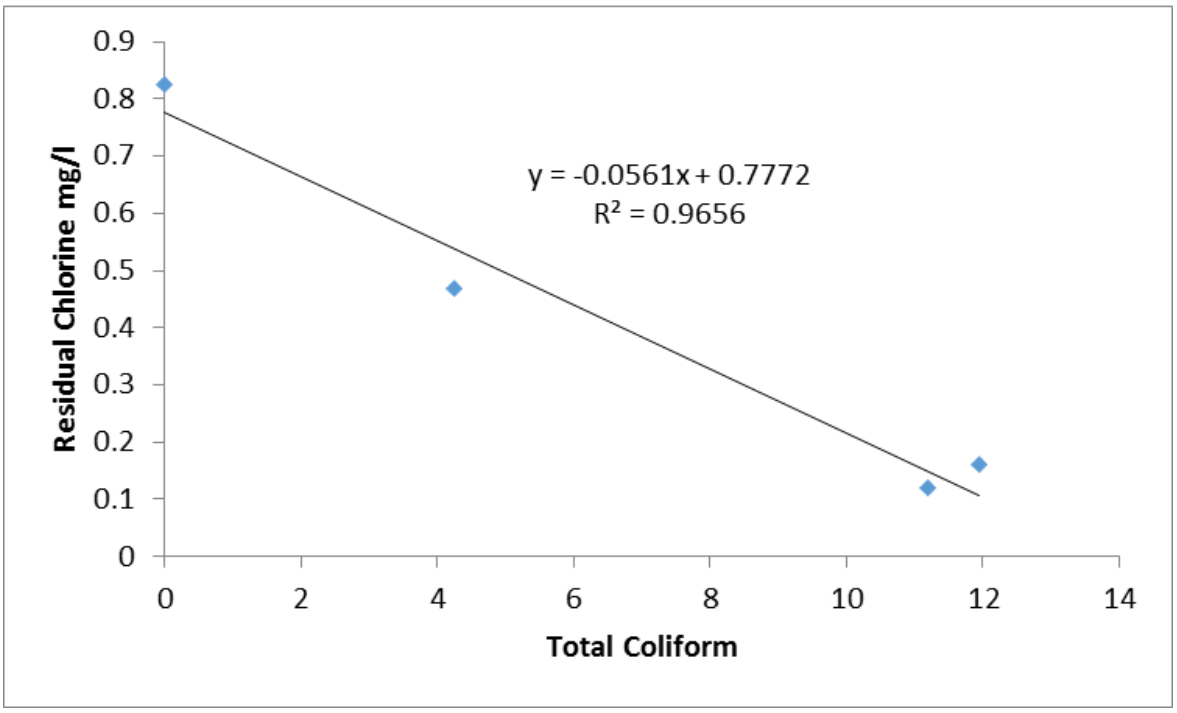


Figure 3.26: Scatter graph showing the correlation between the mean concentrations of residual chlorine and concentrations of total coliform bacteria in water samples collected from the LTP, W-8, W-6 and wider B.S.

The scattered plot of coliform bacterial concentrations versus residual chlorine in Figure 3.26 shows an inverse relationship between the residual chlorine concentration and concentration of total coliform bacteria detected in samples. The concentration of total coliform bacteria tends to increase when the residual chlorine concentration decreased. The highest total coliform bacteria concentrations were found in tap water samples collected from the most remote households in W-6 and the wider Bole subcity (B.S).

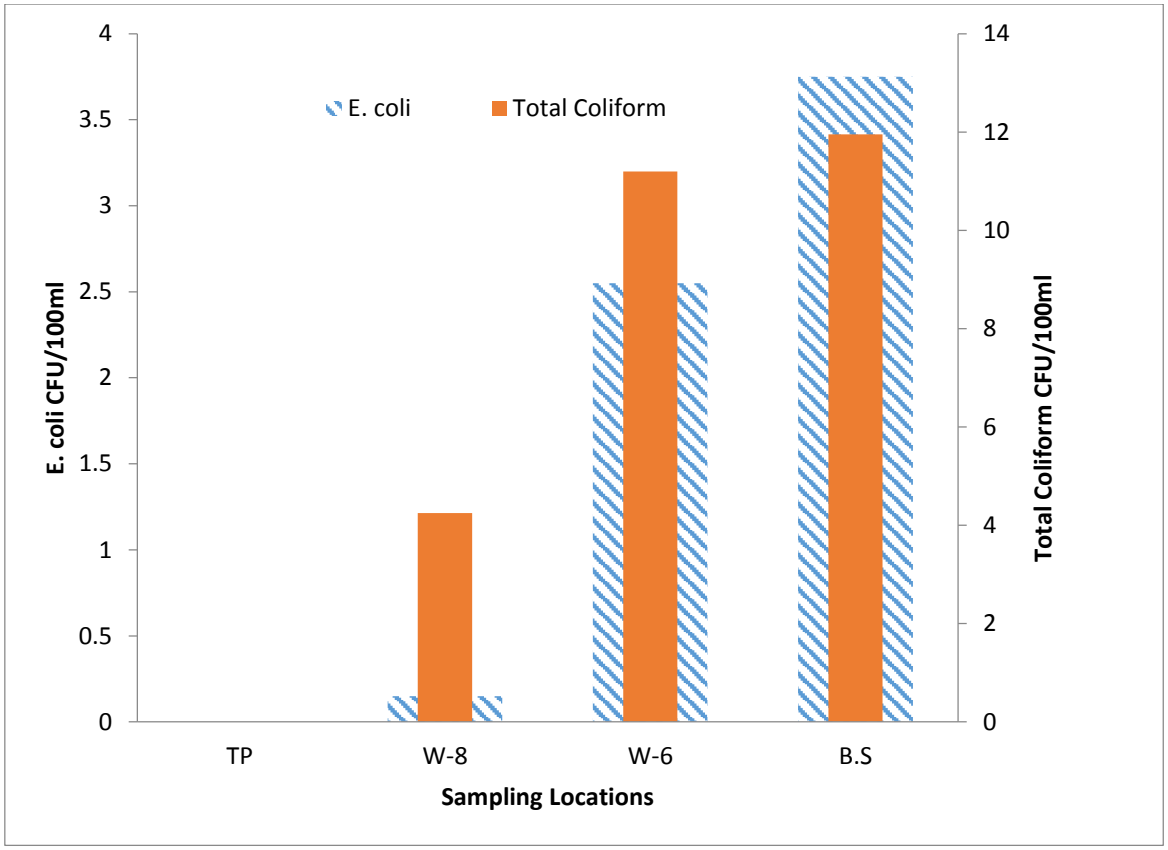


Figure 3.27: Bar graph showing the mean concentrations of both *E. coli* and total coliform bacteria measured in water samples collected from the LTP, W-8, W-6 and wider B.S.

Figure 3.27 shows the mean *E. coli* and total coliform bacteria concentrations detected at all sampling locations. The highest concentrations of both *E. coli* and total coliform bacteria were measured in water samples collected from the most remote households in W-6 and the wider Bole subcity (B.S). In W-8, total coliform bacteria were detected in four samples while *E. coli* was detected in only two tap water samples.

Table 3.8: Summary of water quality results for microbial parameters measured in source and tap water samples collected in Addis Ababa, Ethiopia.

Parameters	Descriptive Statistic	Sampling locations and No. of samples			
		LTP (N=4)	W-8 (N=20)	W-6 (N=20)	Wider B.S (N=20)
E. coli (CFU/100ml)	Maximum	0	2	33	32
	Minimum	0	0	0	0
	Median	0.00	0.00	0.00	0.00
	Mean	0.00	0.15	2.55	3.75
	Std Dev	0.00	0.49	7.32	7.87
Total Coliform (CFU/100ml)	Maximum	0	2	33	32
	Minimum	0	0	0	0
	Median	0.00	0.00	0.00	0.00
	Mean	0.00	0.15	2.55	3.75
	Std Dev	0.00	0.49	7.32	7.87

Table 3.9: The independent samples t-test summary of results. Comparison of mean *E. coli* and total coliform concentrations detected in samples collected in Addis Ababa, Ethiopia.

Group	Parameters	N=4 for LTP, N=20 for W-8, W-6 and wider B.S		
		Compared locations	p-value	Significantly different?
Micro biological	*E. coli*	LTP and W-8	0.553	No
		LTP and W-6	0.501	No
		LTP and B.S	0.360	No
		W-8 and W-6	0.151	No
	Total Coliform	LTP and W-8	0.450	No
		LTP and W-6	0.499	No
		LTP and B.S	0.237	No
		W-8 and W-6	0.363	No

4. DISCUSSION

The first section of this chapter discusses the results from Christchurch City, New Zealand. The second section discusses the results from Addis Ababa City, Ethiopia.

4.1. Effect of Distribution System on Christchurch City Water Supply

The water quality at the Christchurch pump stations and a number of household taps were analysed and compared for a variety of water quality parameters in this study. The water quality results from the source had a number of outliers. The outliers identified in the source water may have been influenced by the earthquake event that occurred in the year 2011. However, the variation in water quality between the source and tap water samples was found to be minimal.

4.1.1. pH

The pH levels measured in the households' tap water were generally lower than the source water. Both median and mean values of pH levels measured in the tap waters were smaller than the source water. The difference in pH mean values between the source and tap water samples was determined to be significant ($p=0.042$). The reason for this significant decrease in pH level in the households' tap water may be attributed to the corrosion of pipeline materials such as cast iron, galvanized steel, asbestos cement and concrete lined steels used in the distribution systems. The decrease in pH in water samples collected at household taps is consistent with study by Lasheen *et al.* (2008) who reported that the pH in drinking water decreased as a result of corrosion taking place in distribution systems.

4.1.2. Conductivity

Similar conductivity values were measured in the source and households' tap water. However, the mean conductivity values determined in the source water (139.41±47.37 µS/cm) were slightly higher than the mean conductivity values in the household tap water samples (133.09±27.63 µS/cm). The high standard deviations in the source water results suggest that the data was variable. As a result, the mean conductivity values of the source water may have been affected by the data variability. This may be attributed to the disturbance or damage of the wells and/or pump-stations during the 2011 earthquake event. The groundwater pumped

for distribution may have been contaminated by rock, soil or construction materials from the pump station.

Although slightly higher mean conductivity values were measured in the source water, from the independent samples t-test, the difference between the source and tap water was determined not to be statistically significant (*p=0.554*). The median conductivity values measured in the source and tap waters were consistent with a median value (130 µS/cm) reported by the Christchurch Groundwater Quality Monitoring Programme (Environment Canterbury, 2013).

Conductivity is a consistent and rapid measurement that may indicate a change in the overall water quality (Kipkemboi, 2012). However, no variation in water conductivity was found in this study that could be attributed to chemical changes caused by the distribution system. This indicates that the distribution system is not likely to be affecting the quality of Christchurch City's water supply.

4.1.3. Turbidity

Nearly 77% of water samples collected from the source had turbidity values of less than 2.5 NTU. 100% of the tap water samples had turbidity values of less than 1 NTU. There were few outliers in the source data. The highest value of turbidity measured in the source water was 9.5 NTU.

The independent samples t-test used to determine that the mean difference in turbidity between the source and tap water samples was not statistically significant (*p=0.11*). Despite this result, an elevated mean (1.51 NTU) turbidity value was calculated for the source water. The highest turbidity values and biggest data outliers were found in the source water 2011 monitoring data. These elevated values could be attributed to the disturbance or damage of the source-wells or pump-stations during the 2011 earthquake event.

The median turbidity values from the source and tap water samples were 0.145 and 0.63 NTU respectively. It is presumed that the slight increase in turbidity from the households' tap water is caused as it passes through the distribution system. This could be due to presence of corrosion products and particles derived from the materials used in the pipes of the water supply distribution system (Bigoni *et al.*, 2014). It may also be attributed to experimental variation as different measuring instruments were used to measure turbidity in the source and tap waters.

Water sourced from the ground with turbidity values greater than 1 NTU can introduce and leave significant quantities of sediment in water distribution systems (Health Canada, 2012). Therefore, the increased turbidity measured in the tap water could be associated with the detachment of corrosion of deposited materials from the internal surfaces of the distribution system. These may have originated from the distribution system or from the source water itself with turbidity greater than 1 NTU.

4.1.4. Nitrate (NO_3)

Both median (5.75 mg/L) and mean (5.81 mg/L) nitrate concentrations in the tap water samples were higher than the median (1.33 mg/L) and mean (3.66 mg/L) nitrate concentrations measured in the source water. The data from the source water samples, which could have been affected by the 2011 earthquake event, were highly variable. However, the independent samples t-test showed that the difference in mean nitrate concentrations between the source and tap water samples were not statistically significant ($p=0.083$).

The naturally occurring nitrate concentrations that are found in groundwater strongly depend on the type soil and geologic situation of the area (WHO, 2003c). According to a study conducted on assessing and tracking nitrate contamination of groundwater systems in Mid-Canterbury, the nitrate concentration for uncontaminated natural groundwater was reported as below 1 mg/L (as nitrate-nitrogen) (Trevis, 2012). The nitrate concentrations measured in the source and tap water samples of this study were close to the nitrate concentrations found naturally in uncontaminated groundwater.

Detection of elevated nitrate concentration in the households' tap water may indicate the intrusion of contaminants in the water supply distribution system (Mechenich & Andrews, 1993). However, despite the slightly elevated nitrate concentrations found in the tap water samples, the concentrations found in both the source and tap water were still very close to the concentrations found naturally in uncontaminated groundwater.

Higher concentrations of nitrate are commonly found in shallow groundwater, while nitrite is less frequently detected in drinking water supplies as it is unstable and continuously oxidized to nitrate in an oxygenated environment (Health Canada, 2013). Therefore, the low level of nitrate found in the source water can be due to the provision of the source water from deep and confined aquifers recharged by Waimakariri River which has lower natural nitrate

concentrations (Hayward, 2002). The elevated nitrate concentrations found in the tap water samples may be attributed to the conversion of nitrite to nitrate, after deep groundwater is pumped and oxygenated in reservoirs before being delivered to customers. In addition, the variation detected may also be associated with the detection limits of the different analysing instruments employed to analyse the source and tap water samples. Thus no elevated nitrate concentrations attributable to intrusion of contaminants in distribution system were found in the households' tap water.

4.1.5. Nitrite (NO_2)

The nitrite concentrations found in the source and households' tap water ranged from 0.017-0.185 mg/L and 0.007-0.059 mg/L, respectively. Like the other parameters tested, extreme outlier nitrite data points were found in the source water. These outliers were also found in the 2011 monitoring data and can be attributed to the damage of source-wells during the 2011 earthquake event. The higher nitrite values have resulted in an elevated mean nitrite value for the source water. The independent samples t-test confirmed that the nitrite concentrations between the source and tap water samples were not statistically significant ($p=0.130$). In addition, the median nitrite concentrations found in the source and household tap waters were very similar.

The naturally occurring nitrite concentrations have been reported to be less than 0.03 mg/L and do not exceed 0.3 mg/L (Health Canada, 2013). The median values obtained from both the source and household tap water samples were similar to the nitrite concentrations naturally found in unpolluted groundwater sources. Generally, there was no variation in nitrite concentrations that can be associated with water quality degradation in the distribution system.

4.1.6. Total Zinc (Zn)

The minimum, maximum, median and mean zinc concentrations measured in the household tap water samples were slightly higher than samples collected from the source. The mean and median zinc concentrations found in the source water were 0.0123 and 0.003 mg/L, respectively. The mean and median values of the household tap water samples were 0.0262 mg/L and 0.0176 mg/L, respectively. The maximum zinc concentrations measured in the source and households' tap waters were 0.086 and 0.200 mg/L, respectively. However, the

independent samples t-test revealed that the mean difference in zinc concentrations between the source and household tap water samples were not statistically significant (*p=0.093*).

The zinc concentrations measured in natural groundwater can vary from 0.01 to 0.04 mg/L. Elevated zinc concentrations can be found in tap water as a result of the leaching of zinc from piping and fittings (WHO, 2003b). The zinc concentrations measured in the source water suggests that the natural zinc concentrations in Christchurch's groundwater supply are very low. The slightly elevated zinc concentrations found in the tap water samples may be attributed to the leaching of zinc from metallic pipelines and fittings that are rarely used in Christchurch City's water supply distribution system.

A study conducted in Mobarakeh, Iran has reported elevated zinc concentrations in tap water (maximum of 5.9 mg/L). The natural zinc concentrations measured in the groundwater, the source of water for the Mobarakeh township, were very low (0.05 mg/L) (Shahmansouri *et al.*, 2010). The elevated zinc concentrations measured in the tap water were likely caused by the aged and leaky metallic (galvanised steel and ductile iron) materials used in the Mobarakeh water supply distribution system.

In contrast to the results reported by Shahmansouri *et al.* (2010), the zinc concentrations found in both the source and tap water samples in this study were minimal. The very low variation in zinc concentrations found between the source and household tap water samples may be attributed to the widespread use of concrete lined steel, polyethylene and polyvinylchloride materials in the water distribution infrastructure (Christchurch City Council Infrastructure Design Standard, 2010). Asbestos cement, ductile iron and cast iron are rarely used.

4.1.7. Total Iron (Fe)

The total iron concentrations measured in source water samples varied from 0.002-1.34 mg/L. The total iron concentrations measured in the household tap water samples varied from 0.02-0.05 mg/L. The median and mean values found in the source water were 0.010 and 0.174 mg/L, respectively. The median and mean values in the households' tap water samples were 0.020 and 0.025 mg/L, respectively. The mean total iron concentrations measured in the source water were significantly higher than the tap water samples (*p=0.049*). The median values measured in the household tap water samples were slightly elevated when compared to the source water samples.

The majority of the greatest total iron concentrations were measured in the source water samples during the 2011 annual monitoring event. These data points may reflect the damage or disturbance of the wells and pump-stations during the 2011 earthquake. As a result of these outliers, an elevated mean iron concentration was found in the source water. It was expected that elevated iron concentrations would be found in the tap water samples.

The iron content of drinking water collected from household taps can be affected by the corrosion of materials used in water supply distribution system (Korfali & Jurdi, 2007). The very slightly elevated median iron concentrations measured in the household tap water samples in this study may therefore be attributed to the internal corrosion of cast iron, ductile iron and galvanised steel pipeline materials that are rarely used in Christchurch City's water supply distribution system.

4.1.8. *E. coli* and Faecal Coliform

No *E. coli* and faecal coliform bacteria were detected in either the source water or household tap water samples collected in Christchurch. The absence of *E. coli* and faecal coliform bacteria in the source water may be attributed to the deep and confined nature of Christchurch's groundwater supply. This supply is secure and less prone to contaminant (animal and human faeces) discharge from the surface (Bourne, 2001). The absence of bacteria in the household tap water samples may be attributed to the good condition, proper inspection and maintenance of the pipelines, and due to the committed work of the Christchurch City Council to supply safe drinking water with secured water supply distribution systems.

4.2. Effects of Distribution Systems on Addis Ababa City Water Supply

Various water quality parameters were analysed in this study. The results of these measurements were compared between the water supplied from the LTP and the household tap water samples collected from different locations within the Bole sub city. Evidence of water quality degradation occurring in the water distribution system was found in the household tap water samples. The water collected from the LTP was found to meet the Ethiopian (WHO) drinking water quality standards.

4.2.1. pH

The median and mean pH levels determined in the water samples collected from the LTP were very similar. In comparison, the median pH values of the water samples collected from household taps located in W-6 were lower. However, the difference was found to not be statistically significant. The pH levels in water samples collected from household taps in W-8 were very close to the pH levels measured in the treated water supply in LTP.

The slight reduction in the pH values measured in tap water samples collected in W-6 may be attributed to the corrosion of aged and cross-connected metallic pipeline materials widely used in the W-6 water supply distribution system. The median pH value determined in tap water samples collected in W-8 was very close to the median value measured in the source water in LTP. This may be due to the close proximity of W-8 to the source water of LTP, or it could also be due to the widespread use of less corrosive materials such as polyvinyl chloride (PVC) and high-density polyethylene (HDPE) which have recently been installed.

The median and mean pH levels collected from the wider Bole subcity (B.S) were found to be slightly higher than the LTP even though they were expected to decrease like the other neighbouring areas. The possible cause for this pH increase may be due to a different water supply. Water samples collected from the periphery of the Bole subcity might have their source in groundwater supplies either from the scattered wells within the city or the Akaki well field. Tap water samples from the wider Bole subcity were collected from households in close and distant proximity to the LTP.

4.2.2. Conductivity

The conductivity of water samples collected from the LTP, W-8, W-6 and the wider Bole subcity (B.S) varied from 100.5-110.6, 101.2-147.5, 115.4-165.5 and 106.4-178.3 µS/cm, respectively. The highest mean (136.70 µS/cm) and median (133.25 µS/cm) conductivity values were measured in the samples collected in the households of W-6, an area which is known for its aged and cross-connected water supply distribution system.

In comparison to the source water in LTP, the maximum conductivities were measured in the household tap water samples collected from W-8, W-6 and the wider Bole subcity (B.S). The highest conductivity measurements were found in water samples collected from remote

households in the W-6 and wider Bole subcity (B.S). In general the conductivity increased as the treated water leaves the LTP and enters into the distribution system. The independent samples t-test revealed that the conductivity differences measured were significantly different between the sample locations (*p=0.001*).

The high mean standard deviation calculated for conductivity measurements of the wider Bole subcity suggests that the data was highly variable. This could be because the household taps sampled in the wider Bole subcity included households in close and distant proximity to the LTP. A number of the taps sampled may have been connected to groundwater sources such as the scattered wells within the city and the Akaki well field. The significant difference in conductivity measured between the LTP and household taps could indicate that the water quality is degraded in the water supply distribution system. This may be caused by the corrosion of old pipeline materials used in the distribution infrastructure. In addition, most of the highest conductivity values were obtained from water samples collected from household taps in W-6 and the wider Bole subcity (B.S) after a supply interruption and reinstatement event. This strongly suggests that contaminants intrude into the pipelines due to the low or negative pressure that occurs inside the water supply infrastructure during interruption events. These may be caused by factors such as power outage and an insufficient water supply. In some areas, water supply availability is restricted to a number of hours per day or days per week. Previous research has suggested that leaky, aged and cross-connected water distribution systems are prone to contaminant intrusion during interruption events. A fall in the internal pipe pressure may cause particulates to be sucked in at this time (Moe & Rheingans, 2006; Nygård *et al.*, 2007).

Water supply disruptions are not desirable and can cause significant water quality degradation in the distribution systems due to reduced pipeline pressures and backflows. The risk is very high in rainfall seasons and in areas where water supply pipelines are connected across drains that hold stagnant water pools (Dagnew *et al.*, 2010). Thus nature of the intermittent water supply and the conditions of the water supply distribution systems of the study areas (W-6 and the wider Bole subcity (B.S)) were comparable to a report by Dagnew *et al.* (2010). In general, the conductivity values obtained in this study indicate that there is water quality degradation that could be attributed to the intrusion of contaminants within the water distribution system.

4.2.3. Turbidity

The turbidity values measured in samples collected from the LTP, W-8, W-6, and the wider Bole subcity (B.S) varied from 0.43-2.50, 0.55-2.01, 0.78-9.30 and 0.55-7.20 NTU, respectively. With the exception of some high turbidity results measured in samples collected from W-6 and the wider Bole subcity (B.S), the median values determined at all sampling locations (LTP, W-8, W-6 and the wider Bole subcity (B.S)) were similar and had values of less than 1 NTU. The independent samples t-test also revealed that there were no statistically significant differences in turbidity between the LTP and tap water samples collected from W-8, W-6 and the wider Bole subcity (B.S).

The greatest turbidity value measured at the LTP was 2.5 NTU. This was found in a sample collected in early July when the level of water in the dam was at its lowest level. As a result, the raw water from the dam was delivered with the third intake valve. The elevated turbidity result measured in early June could be due to the inability of the treatment plant to treat the turbid raw water that was most likely sourced from the bottom of the dam.

A number of highly turbid samples were collected from household taps in the W-6 and the wider Bole subcity (B.S) after supply interruption and reinstatement events. These turbidity results suggest sediment intrusion, which may be caused by a fall in internal pipe pressure in the leaky, aged and cross-connected water supply distribution systems common in W-6 and the wider Bole subcity (B.S).

The results between W-8 and W-6 were compared. 65% the tap water samples collected in W-6 had turbidity values greater than 1 NTU. In comparison, 85% of the tap water samples in W-8 had turbidity values less than 1 NTU. The differences in turbidity were also found to be statistically significantly different ($p=0.024$). The high turbidity values occurring in W-6 may be attributed to the supply interruption and intrusion of sediments. The household taps in W-8 receives water from the supply network before it is distributed to other areas. Supply interruption was found to not be a problem in W-8. The presence of continuous water supply can prevent pipe-pressure fall and also prevent the intrusion of external contaminants even if there is a problem with the distribution infrastructure.

The turbidity results reported in this study are consistent with a study by Bigoni *et al.* (2014) who reported higher turbidity values in samples collected from household service connections

than from main transmission lines close to the source water. It was also reported that corrosion products, such as iron particles derived from steel pipes used in the distribution systems, were the cause of elevated turbidity values.

4.2.4. Nitrate (NO_3)

The mean and median nitrate concentrations determined from water samples collected from the LTP, W-8, W-6 and the wider Bole subcity (B.S) was similar. There were no large variations in the maximum, minimum, median and mean nitrate concentrations measured in this study. There was no evidence of nitrate contamination after treated water from the LTP enters into the distribution system. The independent samples t-test also confirmed that the differences in nitrate concentrations between sampling locations were not significantly different. However, the lack of informative results and clear evidence of nitrate contamination in this study could be attributed to the use of NitraVer® 5 nitrate reagent powder pillows which had expired in 2008. Therefore, based on the results obtained from this study, it is difficult to draw a conclusion on the status of nitrate concentrations and any possible sources of nitrate contaminants in the study areas.

In a similar study conducted by Worku *et al.* (1999) nitrate concentrations were reported to range from 9.1-41.0 mg/L in the tap waters of Addis Ababa. The mean nitrate concentration in the treated water from the LTP was 12.8 mg/L. The tap water samples were collected from households in the wider city of Addis Ababa City. The households sampled also had different supplies. In another recent study by Seda *et al.* (2013), a mean nitrate concentration of 1.67±0.045 mg/L was reported in tap water samples collected in Addis Ababa. There is still lack of informative nitrate results in these studies. The nitrate concentrations reported in 1999 were higher than those recently reported in 2013. It was expected that the nitrate concentrations would increase over time as a result of anthropogenic disturbance. The lack of consistency in nitrate concentrations in these two reports and this study suggests that there is lack of certified laboratories and analytical instruments that are capable of consistent nitrate analysis.

4.2.5. Nitrite (NO_2)

Nitrite concentrations measured in the source water of the LTP ranged from 0.016-0.024 mg/L. The median and mean values were similar at 0.02 mg/L. The nitrite concentrations measured

in the household tap water samples of W-8, W-6 and the wider Bole subcity (B.S) varied from 0.01-0.04, 0.030-0.007 and 0.022-0.009 mg/L, respectively.

The median and mean nitrite concentrations were similar in all sampling locations. The independent samples t-test also confirmed that the mean differences between sampling locations were not significantly different. Nevertheless, in comparison to the nitrite concentrations measured at the LTP, a slight reduction in nitrite concentration was observed between the source and the tap water samples. The reason for this reduction in the distribution system is unclear. It was expected that nitrite would increase as a result of the problems with the water supply distribution infrastructure in the study areas. However, there are ways in which nitrite could be reduced in the distribution system. The exposure of the water supply systems to sunlight could increase the water temperature and reduce dissolved oxygen. This is common in the study areas. The reduction of dissolved oxygen could promote denitrification in the distribution system. However, this is beyond the scope of this research and warrants further investigation.

The mean and median nitrite concentrations in samples collected from the wider Bole subcity (B.S) were found to be elevated compared to values from W-6 and W-8. This could be because a number of water samples collected from households in the periphery of the Bole subcity were connected to the groundwater supply networks. Examples include the Akaki well field or scattered wells within the city. These water resources have been reported to be contaminated from low cost sanitation facilities such as pit latrines (Abay, 2010).

4.2.6. Total Zinc

Zinc concentrations measured from LTP, W-8, W-6 and the wider Bole subcity (B.S) were ranged from 1.11-1.26 mg/L, 1.18-1.58 mg/L, 1.21-1.49 mg/L and 1.19-1.47 mg/L, respectively. The median and mean values found in the source water samples from the LTP were similar. Higher median and mean zinc concentrations were measured in the household tap water samples. Increased zinc concentrations were measured in household tap water samples from all areas in all descriptive statistics (maximum, minimum, mean and median results). The difference in zinc concentrations measured in samples from the LTP and household taps of W-8, W-6 and the wider Bole subcity (B.S) were significantly different ($p=0.005$, <0.001 and 0.002, respectively).

Zinc concentrations in household tap water are typically much higher as zinc is leached from metallic piping and fittings used in the water distribution systems. The natural zinc concentrations in uncontaminated drinking water are usually very low (WHO, 2003b). The reason for the dramatic increase in zinc concentrations after treated water enters the distribution system may be attributed to the leaching of zinc from galvanised steel and ductile cast iron materials that are predominantly used in Addis Ababa's water supply distribution systems. The concentrations of zinc measured in the source water in this study are higher than the concentrations that usually occur in uncontaminated drinking water (WHO, 2003b). In addition, the zinc concentrations found in tap water samples were higher than those reported by Seda *et al.* (2013) and Worku *et al.* (1999). One possible reason for the discrepancy in iron concentrations could be due to error of the analysing instrument used in the EKHCDP laboratory. Another reason for the higher zinc concentrations could be due to contamination of the source water with zinc enriched industrial and agricultural chemical wastes which may have developed and increased over time within the catchment of the dam. The reason for this possibility is beyond the scope of this research.

Despite of the lack of consistency in the raw data, the mean zinc concentration difference between LTP and those from household taps was found to be consistent with a study by Worku *et al.* (1999) who reported an elevated mean zinc concentrations in tap water samples (0.5 mg/L) when the mean zinc concentrations in the treated water was is very low (0.115 mg/L). The zinc concentrations measured in the areas of W-8 and W-6 were not statistically significantly different ($p=0.387$). This indicates that the water supply distribution systems in W-8 are also leaching zinc, regardless of the recent and modern water supply distribution system used in the areas. The maximum zinc concentrations measured at W-8 were found in water samples collected from a single household's tap. Similarly, the maximum total iron concentration was also obtained from this tap. These water samples may have been collected from a tap connected to an elevated metallic storage tank that is galvanized with zinc. Alternatively, the household's pipeline might also have been old and corroded.

In general, despite the unusual zinc concentrations found in all sampling locations, the significant difference in zinc concentrations between the source and households' tap water suggests that the distribution system infrastructure is affecting the households' drinking water quality.

4.2.7. Total Iron

The total iron concentrations measured in the source water from the LTP varied from 0.023-0.039 mg/L. The iron concentrations measured in the tap water samples from W-8, W-6, and the wider Bole subcity (B.S) varied from 0.006-0.735, 0.028-0.538 and 0.012-0.252 mg/L, respectively. The median and mean values determined in the LTP were significantly below the concentrations normally found in uncontaminated drinking water (WHO, 2003b). However, both the median and mean iron concentrations were increased in the household tap water samples of W-8, W-6 and the wider Bole subcity (B.S). The independent samples t-test revealed that the mean differences in the total iron concentrations measured in the LTP and household tap water samples of W-6 and the wider Bole subcity (B.S) were statistically significant ($p=0.006$ and 0.002, respectively).

The elevated iron concentrations measured in the tap water samples of W-6 and the wider Bole subcity (B.S) can be attributed to the corrosion of the cast iron and galvanized iron pipe materials commonly used in the water supply distribution systems of W-6 and the remote areas of Bole subcity. The higher concentration detected indicate that drinking water quality deteriorates in the water supply distribution systems of the remote areas of the Addis Ababa. Water samples collected from household taps close to the LTP showed less variation in iron concentrations.

The greatest iron concentrations (reported as outliers) from W-6 and the wider Bole subcity (B.S) were obtained from tap water samples collected after supply interruption and reinstatement events. These high results can be attributed to the rapid corrosion of pipes resulting from intermittent supply. The emptying of pipelines allows for the intrusion of air/oxygen that enhance the internal corrosion of pipelines (Sridhar, 2013). It can also be attributed to the intrusion of iron-bound environmental contaminants from the outside of leaky, aged and cross-connected pipelines common in these areas. As households are uncertain when water will be supplied, faucets are often kept open during supply interruptions and it is common to hear air sound that comes out through the pipe's faucet. This can indicate that the pipeline has a leakage at a distance very close to the household. Pipeline pressures can drop in the event of supply interruptions and allow external contaminants to enter the distribution system.

The independent samples t-test was used to demonstrate that the mean differences in iron concentrations between LTP and W-8, W-8 and W-6 were not significantly different. The possible reasons for this lack of statistically significant difference between LTP and W-8 include:

- The close proximity of W-8 to the water source (LTP). This reduces the retention time of water in the distribution system and corrosion in the pipelines. The water supply in W-8 is also continuous. This prevents the fall of pressure within the pipelines and the intrusion of contaminants and air that degrades water and enhances corrosion of the internal pipe-walls, respectively.
- It may also be due to the recent use of modern materials in the development of new pipelines which are less susceptible for corrosion.

The lack of significant differences in the mean iron concentrations between W-8 and W-6 suggested that corrosion is still occurring in the W-8 water supply distribution system. A number of high iron concentration samples were collected from households in W-8. The greatest concentrations of iron measured in this study were collected from a single household tap water sample in this area. The reason for this elevated concentration may be because the water sample was collected from a tap connected to an elevated metallic storage tank. It may also be caused by a very old metallic pipe which has been highly corroded.

In general, significantly higher iron concentrations were found in most of the household tap water samples. These elevated iron concentrations may be attributed to corrosion taking place inside the old galvanised steel and ductile cast iron pipeline materials used in the water supply distribution system. Results from this study were also comparable to a similar study conducted by Shahmansouri *et al.* (2010). It was determined in their study that corrosion of galvanised steel and ductile cast iron in the distribution system contributed to iron contamination of the piped water.

4.2.8. Residual Chlorine

Residual chlorine levels were measured in the water leaving the LTP. The concentrations measured were almost constant with a mean value of 0.83±0.05 mg/L. The mean residual chlorine levels measured in the household tap water samples of W-8, W-6 and the wider Bole subcity (B.S) were 0.47±0.08, 0.12±0.11, and 0.16±0.17 mg/L, respectively. In this study,

residual chlorine levels dramatically declined after the treated water left the LTP and entered into the distribution system. The degradation in the mean residual chlorine in all household tap water samples (W-8, W-6, and the wider Bole subcity (B.S)) were found to be significant (*p=<0.001*). The residual chlorine levels measured in the remote households of W-6 and the wider Bole subcity (B.S) were minimal, with levels ranging from <DL-0.3 and <DL-0.6 mg/L, respectively. The concentrations measured in W-8, which is relatively close to the LTP, were in the range of 0.3-0.65 mg/L.

A residual chlorine concentration between 0.8-1 mg/L is used to disinfect bacterial contamination that may appear in the distribution system. For this reason, a mean value of 0.8 mg/L residual chlorine is maintained in the post chlorination process. However, the residual chlorine rapidly degrades when the treated water enters into the distribution system. In some households, especially in the W-6 and the wider Bole subcity (B.S) areas, residual chlorine appeared to drop as low as less than DL of the instrument. A possible reason for this rapid drop in concentration could be due to the breakdown of residual chlorine by microbes attached to biofilms, corrosion in pipes and water aging in distribution system. These are known to be present on the inner surfaces of old, leaky and cross-connected pipelines common in water supply distribution systems of the study areas (W-6 and the wider Bole subcity (B.S)). Another possible reason could be the intermittent supply of water that can lead to negative pipe-pressure and intrusion of contaminants. These contaminants could further reduce the residual chlorine in the distribution system. The distance of the household to the LTP and increasing time spent in water storage reservoirs and pipes could also deplete the residual chlorine before it reaches the household taps.

These assumptions are similar to study findings by Ecura *et al.* (2011) who reported that rapid deterioration of residual chlorine occurred in the water distribution network of Kampala, Uganda. This was a result of, the distance from the treatment plant, the intermittent supply leading to contaminant intrusion, and growth of bacteria in pipes due to the depletion free residual chlorine. In addition, a study by Kumpel and Nelson (2013) compared the microbial water quality in an intermittent and continuous piped water supply. It was reported that a significantly higher proportion of samples collected from a continuous supply met the minimum standard for residual chlorine concentrations when compared to samples from intermittent water supplies.

All tap water samples from W-8 had appreciable residual chorine concentrations ranging from 0.3-0.65 mg/L. One possible explanation could be the short distance between W-8 and the LTP. The distance of piping affects the length of time the water exists in the distribution system. Longer periods will enhance the depletion of residual chlorine before reaching the household taps. Another possible explanation could also be due to the continuous water supply. This reduces water aging in the distribution system and limits the depletion of residual chlorines. The results from this study are also consistent with Ecura *et al.* (2011) who noted residual chlorine degrades as the distance the water travels from the treatment plant increases.

A supplementary correlation analysis was conducted between the distance from the LTP and the degradation in residual chlorine in water samples collected from household taps. A coefficient of determination (r^2=0.72) or linear correlation coefficient (r=0.85) was found, showing that there is a strong correlation between degradation of residual chlorine and distance from LTP. Households located far away from the LTP, terminal and reservoirs were found to have little or no residual chlorine in their tap water. Households located in close proximity to the LTP were found to have residual chlorine concentrations higher than the minimum limits.

4.2.9. *E. coli* and Total Coliform

No *E. coli* or total coliform bacteria were found in the water samples collected from the LTP. The absence of both *E. coli* and total coliform bacteria in the treated water is due to the pre-chlorination application that kills any bacteria delivered with the raw water. The treated water also had a mean of 0.8 mg/L residual chlorine due to the post-chlorination process.

No *E. coli* bacteria were found in the majority of the water samples collected from W-8. Only two samples had *E. coli* counts of less than 2 CFU/100ml. Similarly, the majority of samples collected from W-8 were free of coliform bacteria. Four samples (20%) had total coliform bacteria ranging from 4-40 CFU/100ml. In W-8, all tap water samples with *E. coli* had total coliforms present.

A median concentration of 0 CFU/100ml of *E. coli* was detected in W-6 and the wider Bole subcity (B.S). However, elevated *E. coli* concentrations ranging from 2-33 and 2-32 CFU/100ml were detected in 35% and 40% of the water samples collected from W-6 and the wider Bole subcity (B.S), respectively. The concentrations of total coliform bacteria ranged from 4-144 and 1-71 CFU/100ml in W-6 and the wider Bole subcity (B.S), respectively. The

majority of *E. coli* and total coliform bacteria were detected in samples collected from W-6 and the wider Bole subcity (B.S) after supply interruption and reinstatement events.

The occurrence of *E. coli* and total coliform bacteria in tap water samples can be attributed to contamination of the distribution system as no bacteria are found in the source water (Kumpel & Nelson, 2013). The median *E. coli* and total coliform counts found at all sampling locations was 0 CFU/100ml. However, substantial concentrations of bacteria were detected in household tap water samples and suggest that there is water quality degradation in the water supply distribution system.

The higher concentrations detected in W-6 and the wider Bole subcity (B.S) may be attributed to the aged, leaked and cross-connected water supply distribution systems which are common in these areas. Many of the samples were collected from these areas after supply interruption and reinstatement events. Leaky and cross-connected pipelines could be contaminated by the external environment due to negative pressures or suction occurring at these times.

The microbial water quality results measured in this study strongly agree with a study conducted by (Kumpel & Nelson, 2013). It was reported that bacterial contamination is more frequent in intermittent water supply networks when compared to those continuously supplied. The study by Kumpel and Nelson (2013) also suggests that bacterial contamination in an intermittent water supply could be caused to the intrusion of contaminants from the environment when the water supply to pipelines is turned off. This causes negative pipe-pressure events and causes problems when combined with cross-connection pipelines. These issues are common in Addis Ababa and are the main problems within the study areas.

The tap water samples showed *E. coli* and total coliform bacteria had very low or no residual chlorine concentrations. Similarly, studies by Kumpel and Nelson (2013) in Hubli-Dharwad, India and Ecura *et al.* (2011) in Kampala, Uganda have also reported frequent and elevated bacterial contamination in tap water samples with residual chlorine concentrations below the recommended guideline values. Zero CFU/100ml bacteria are reported in water samples retaining good residual chlorine concentrations in both studies. The results reported in this study are similar.

E. coli and total coliforms were detected in a small number of water samples collected in W-8. The residual chlorine concentrations in these samples were high enough to kill the bacteria in

the samples. This suggests that the intrusion of contaminants may be occurred at a point close to the end-users. This may also be attributed to the survival of the bacteria due to inactivation of the residual chlorine in the samples with sodium thiosulfate. Another possible explanation could be due to the growth of bacteria in biofilms where they are protected from inactivation (Kumpel & Nelson, 2013).

The reduced concentrations of *E. coli* and total coliform bacteria found in W-8 may be attributed to the tidiness of the environment and the absence of cross-connected pipelines. A continuous water supply will also prevent negative pipe-pressures and the intrusion of external contaminants. The reduced concentrations may also be due to the close vicinity of the households to the LTP and the higher residual chlorine concentrations in the distribution system.

Results obtained from this research project in Addis Ababa City have clearly agreed with the water quality issues that have been claimed by customers. During the author were in the Addis Ababa laboratory, customers provided water samples to be tested after dark and turbid water flowing from taps after supply disruption and reinstatement events (Figure 4.1). Samples were also tested for physiochemical parameters such as pH, conductivity, turbidity, nitrate, nitrite and total iron concentrations to generate evidence of water quality deterioration in the distribution system (Appendix G). All the results for the measured parameters (conductivity, turbidity, nitrate, nitrite and total iron concentrations) were found to be very high. Among these parameters, conductivity and turbidity had very high results ranged from 125.5-571.9 µS/cm and 15.5-53.0 NTU, respectively.

In addition to this study, water quality parameters such as residual chlorine, *E. coli* and total coliform bacterial counts were routinely monitored by the AAWSA. Some raw data from this monitoring are presented in Appendix H. From the daily and monthly results, tap water samples collected from households connected to different source supplies have shown positive *E. coli* and total coliforms while their residual chlorine concentrations were less than detection limit (DL), and vice versa. In addition, residual chlorine, *E. coli* and total coliform results in tap water samples also showed seasonal variation in microbial contamination. Tap water samples collected in rainy months showed elevated positive *E. coli* and total coliforms and less than DL

residual chlorines than samples collected in dry months. Thus, occurrence of an elevated *E. coli* and total coliforms during the rainy season and disappearance in residual chlorine could be a strong evidence for intrusion of contaminants through water supply distribution systems.

The AAWSA results detailed in Appendix H are also consistent with those reported by Kumpel and Nelson (2013) who found higher concentrations of bacteria in tap water samples collected during the rainy season. The high concentrations of bacteria may also be the result of contaminant intrusion into the pipe networks exposed to intermittent water supplies. This is also a major problem in Addis Ababa City's water supply system.

Figure 4.1: Household tap water samples collected and provided by customers, after supply interruption and reinstatement events.

4.3. Compliance with Drinking Water Quality Standards

Drinking water delivered to customers of Christchurch and Addis Ababa Cities should maintain a good standard of quality from the source to the households supplied. The water provided should not degrade in quality as it passes through the distribution system. Therefore, drinking water quality compliance assessments should be undertaken between the source and household end users. The water tested should meet physical, chemical and biological standards (maximum acceptable limits) set by the nation or health organisations involved.

For the purposes of this research, the water quality data generated for samples collected in Christchurch and Addis Ababa were assessed for their compliance with drinking water quality standards.

4.3.1. Assessment for Christchurch City

Christchurch City's drinking water as collected from household taps was tested for a range of physical, chemical and biological parameters in this study. The data generated was then assessed for compliance against the Drinking Water Standards of New Zealand (DWSNZ) (Table 4.1). Annual monitoring results were obtained from the Christchurch City Council (CCC) for the source water for the years 2010–2014. The data was available for all water quality parameters at the selected wells/pump stations of interest over this period.

Table 4.1: Compliance assessment of physical and chemical parameters with DWSNZ. Non-compliant results and percentages of compliance are highlighted in bold.

	Source water (N=26)		Tap water (N=27)		MAV	Percentage of compliant samples (%)	
Parameters	Min-Max	Mean	Min-Max	Mean		Source water	Tap water
pH	**6.90**-8.25	7.60	**6.53**-8.06	7.34	7.0-8.5	**92%**	**74%**
Conductivity	87.0-323.0	139.4	100.4-221.0	133.09	400-1200	100%	100%
Turbidity	0.06-**9.50**	1.51	0.21-0.95	0.62	2.5	**77%**	100%
Nitrate	0.27-28.73	3.66	1.99-11.93	5.81	50	100%	100%
Nitrite	0.017-0.190	0.050	0.007-0.059	0.033	3	100%	100%
Total Zinc	0.001-0.090	0.012	0.002-0.200	0.026	1.5	100%	100%
Total Iron	0.002-**1.340**	0.170	0.020-0.050	0.025	0.2	**80.77%**	100%

Note: Units for conductivity in µS/cm, turbidity in NTU and all the rest parameters are in mg/L.

Physical Parameters

Physical water quality parameters such as pH, conductivity and turbidity were assessed for compliances against the reference ranges detailed in the DWSNZ (Table 4.1). The mean pH, conductivity and turbidity values for source and household tap waters were found to mostly comply with the maximum acceptable values set by the DWSNZ.

100% of samples complied with the DWSNZ for conductivity in samples collected from both the source and household taps. Fewer samples complied with standards for pH and turbidity. As stated in DWSNZ by the Ministry of Health (2008), a guideline pH of 7-8.5 is recommended

for drinking water. This range is very strict in reference to other drinking water standards. For example, the World Health Organisation (WHO, 2008) recommends pH values between 6.5-8.5. As a result, 92% and 74% of water samples met the DWSNZ standard in samples collected from the source and household taps, respectively.

The tap and source water samples exceeding the DWSNZ had pH values of 6.9 and 6.53, respectively. These samples would have met the WHO drinking water standards. A possible reason for pH level below the recommended range could be due to the corrosion of pipeline materials used in the distribution system as noted earlier.

Approximately 77% of the water samples collected from the wells/pump-stations complied with the DWSNZ standards for turbidity (2.5 NTU). 100% of the tap water samples had turbidity values much lower than the maximum acceptable value (MAV). The majority (33%) of the source water samples exceeding the turbidity standards were collected by the CCC in 2011. A possible reason for these results could be due to damage caused to the source-wells and pump stations during the 2011 earthquake event.

Chemical Parameters

Chemical parameters including nitrate, nitrite, total zinc and total iron were assessed for complacence against the reference ranges detailed in the DWSNZ. This is summarised in Table 4.1. All water samples collected from the source and household taps were found to meet the DWSNZ for nitrate (NO_3), nitrite (NO_2) and total zinc. The majority of samples were found to have concentrations much lower than the MAV set by the DWSNZ. However, approximately 20% of source water samples exceeded the MAV for iron concentration.

The majority of source water samples exceeding the total iron standards were collected by the CCC in 2011. Again, this could be due to the earthquake event of 2011. The disturbance of rock, soils, as well as the degradation of supple infrastructure, may have contributed to the elevated iron concentrations measured in the groundwater.

Microbiological Parameters

The Drinking Water Standards for New Zealand state that no *E. coli* or faecal coliforms should be detected in 100 ml samples of drinking water (Ministry of Health, 2008). To test compliance with these standards, both *E. coli* and faecal coliform bacteria were tested for in the source and

household tap water samples. No *E. coli* or faecal coliform bacteria were detected in any samples.

100% of source and household tap water samples complied with the DWSNZ standards for bacterial contamination. This confirms that Christchurch City's drinking water, which is sourced from deep and confined aquifers, is naturally pure and is delivered to customers' in a water supply distribution system that is functioning well.

4.3.2. Assessment for Addis Ababa City

Water samples were collected from the LTP, W-6, W-8 and the wider Bole subcity to characterise the possible effect of the water supply distribution systems on household drinking water quality in Addis Ababa. The data generated from these samples was used to assess the compliance of samples against relevant drinking water standards. All results and their means were considered for compliance against the maximum acceptable values (MAV) set by the Ethiopian (WHO) standards. The overall assessment is also presented in Table 4.2.

Table 4.2: Summary for overall the physical, chemical and microbiological parameters used in the compliance assessment of water samples collected in Addis Ababa, Ethiopia. The Ethiopia Ministry of Water Resources (2002) and WHO (2008) drinking water quality standards are presented. Non-compliant results and percentages of compliance are highlighted in bold.

	Number of samples from sampling locations: (LTP, N=4), (W-8, N=20), (W-6, N=20) and (the wider B.S, N=20)								Ethiopia (WHO)	Percentage of compliant samples (%)			
	LTP		W-8		W-6		B.S						
Parameters	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	**MAV**	LTP	W-8	W-6	B.S
pH	6.6-7.36	7.01	**6.46**-7.36	6.97	6.46-7.42	6.93	6.46-7.46	7.08	6.5-8.5	100%	**95%**	**95%**	**95%**
Conductivity	100.50-110.60	106.15	101.20-147.50	121.26	115.40-165.50	136.70	106.40-178.30	128.91	400-1200	100%	100%	100%	100%
Turbidity	0.43-2.50	1.17	0.55-2.01	0.84	0.78-**9.30**	2.13	0.55-**7.20**	1.48	5	100%	100%	**85%**	**95%**
Nitrate	17.16-33.00	22.77	15.62-24.20	20.91	17.16-31.68	22.78	16.72-33.44	22.44	50	100%*	100%*	100%*	100%*
Nitrite	0.020-0.024	0.020	0.010-0.040	0.020	0.010-0.030	0.015	0.010-0.022	0.020	3	100%	100%	100%	100%
Total Zinc	1.11-1.26	1.17	1.18-1.58	1.34	1.21-1.49	1.37	1.19-1.47	1.34	5	100%	100%	100%	100%
Total Iron	0.02-0.04	0.03	0.01-**0.74**	0.14	0.03-**0.54**	0.13	0.01-0.25	0.08	0.3	100%	**90%**	**85%**	100%
RC	0.80-0.90	0.83	0.30-0.65	0.47	0-0.30	0.12	0-0.60	0.16	5 & 0.2**	100%	100%	**30%**	**30%**
E. coli	0.0-0.0	0.0	0-2	<1	0-33	>2	0-32	>3	0 CFU/100ml	100%	**90%**	**65%**	**60%**
TC	0.0-0.0	0.0	0-40	>4	0-144	>11	0-71	>11	0 CFU/100ml	100%	**80%**	**55%**	**40%**

Note: The unit for all chemical parameters is mg/L. Conductivity is measured in µS/cm. Both *E. coli* and TC are in CFU/100ml. * Results may not be representative due to the use of expired analytical reagent powder pillows. ** The WHO recommend 5 mg/L chlorine in pre-chlorination processes and a minimum of 0.2 mg/L residual chlorine in post-chlorination. 0.8 mg/L mean residual chlorine was maintained at the LTP in post-chlorination.

Physical Parameters

A summary of the data used in the compliance assessment for the physical water quality parameters tested at all sampling locations in Addis Ababa (LTP, W-8, W-6 and the wider Bole subcity (B.S)) is presented in Table 4.2. Samples were tested for pH, conductivity and turbidity.

The range and mean water quality results from water tested at the source, the LTP, show 100% compliance for pH, conductivity and turbidity. A single sample was found to have a higher turbidity of 2.5 NTU. However, this result was still under the acceptable limit for turbidity of 5 NTU. This sample was collected in early July, when the level of water in the dam was at its lowest level. The delivery of raw water from the bottom of the dam could reduce the efficiency of the treatment plant.

The mean pH, conductivity and turbidity values measured from household taps in W-8, W-6 and the wider Bole subcity were within the limits set by the Ethiopia (WHO) drinking water standards (Table 4.2). Few non-compliant samples for pH and turbidity were collected from household taps in W-6 and the wider Bole subcity. The majority of these samples were collected after supply interruption and reinstatement events.

The range and mean conductivity values measured at all sampling locations in Addis Ababa were much lower than the 400-1200 µS/cm range recommended by the Ethiopian (WHO) drinking water standards. However, the conductivity values measured in tap water samples collected in W-6 and the wider Bole subcity were significantly higher than those measured in water collected from the LTP. High conductivity values do not in themselves present a health risk. However, increased values in water may indicate contamination in the supply infrastructure.

Chemical Parameters

A summary of the data used in the compliance assessment for the chemical water quality parameters tested at all sampling locations in Addis Ababa (LTP, W-8, W-6 and the wider Bole subcity (B.S)) is presented in Table 4.2. Samples collected were tested for concentrations of nitrate, nitrite, total zinc, total iron and residual chlorine.

The range and mean water quality results from water tested at the source, the LTP, show 100% compliance for all chemical parameters. The mean and range of nitrate, nitrite and total zinc

concentrations in the household tap water samples of W-8, W-6 and the wider Bole subcity (B.S) were in 100% compliance with the Ethiopian (WHO) drinking water standards. Nitrate concentrations measured at all sampling locations were similar even though a large variation between the water sourced from the LTP and the household tap water samples was expected. A possible reason for the lack of apparent nitrate contamination may be due to the expired nitrate reagent powder pillows used in the AAWSA laboratory as noted earlier. All zinc concentrations complied with the drinking water standards.

The mean total iron concentrations measured in the household tap water samples collected in W-8, W-6 and the wider Bole subcity (B.S) were much lower than the recommended values for drinking water. A number of exceedances were found in household tap water samples collected from W-8 and W-6 (Table 4.2). The 15% exceedance in total iron concentration measured in W-6 was found in a tap water sample collected after a supply interruption and reinstatement event. The differences in iron concentrations measured between the LTP and W-6 was significant. The exceedance from W-8 was measured in a tap water sample collected from a single household. The turbidity from this particular household was also found to be above 1 NTU while the turbidity measured from the rest of the neighbouring households were less than 1 NTU.

A maximum of 5 mg/L of chlorine may be added to raw water in treatment plants to disinfect and control the growth of algae inside the treatment compartments (WHO, 2008). In order to disinfect any bacterial contamination that might occur within the distribution systems, the WHO also recommends that treated water maintains a concentration of 0.2-1 mg/L residual chlorine concentration. A mean residual chlorine concentration of 0.8 mg/L was maintained in water provided by the LTP. However, rapid degradation of this residual chlorine was observed after treated water leaved the LTP and entered into the distribution system. The concentrations found in most household taps were less than the minimum recommended concentration of 0.2 mg/L.

W-8 is located in relatively close proximity to the LTP treatment plant. The residual chlorine concentrations found in all water samples collected from W-8 were well above the minimum concentrations recommended by the Ethiopia (WHO) drinking water standards (Table 4.2). In contrast, the residual chlorine concentrations found in the household tap water samples collected in the remote areas of W-6 and the wider Bole subcity were below the minimum

concentrations recommended for household tap water. The residual chlorine concentrations reported for W-6 and the wider Bole subcity (B.S) failed to comply with the Ethiopian drinking water standards (WHO). Only 30% of the 20 total tap water samples collected from households in W-6 and the wider Bole subcity (B.S) complied with the standards.

Microbiological Parameters

Both *E. coli* and total coliform bacteria were used for the microbiological compliance assessments of Addis Ababa's drinking water quality. A summary of results for this assessment is also presented in Table 4.2.

According to the Ethiopia Ministry of Water Resources (2002) and the WHO (2008), no *E. coli* or total coliform bacteria should be found in any 100 ml sample of water. All water samples collected from the LTP showed 100% compliance (0 CFU/100ml sample of water) for both *E. coli* and total coliform bacteria (Table 4.2). However, there was less compliance in tap water samples. Especially those collected from households far away from the treatment plant. Samples collected from W-6 and the wider Bole subcity (B.S) were less compliant with the drinking water quality standards.

E. coli and total coliform bacteria were found in tap water samples collected from W-6 and the wider Bole subcity. This is likely due to lower residual chlorine concentrations in the samples. In general, the mean total coliform bacteria detected in W-6 and the wider Bole subcity (B.S) was >11 CFU/100ml. The mean concentrations of *E. coli* measured in samples collected from W-6 and the wider Bole subcity were >2 CFU/100ml and >3 CFU/100ml, respectively. Few bacteria were found in samples collected from W-8. This is likely due to the appropriate concentrations of residual chlorine measured in these samples which is enough to kill bacteria.

In conclusion, tap water samples collected from all sampling locations were not in complete compliance with the Ethiopian drinking water standards (WHO) which is 0 CFU/100ml sample. Most of the non-complying samples were collected in household tap water samples collected in remote areas after supply interruption and reinstatement events. These concurrent events (supply interruption, reinstatement and bacterial detection) may be the major sanitation problem in Addis Ababa. The detection of bacteria in most water samples collected after supply interruption and reinstatement events confirms that there is water quality degradation in the water supply system of Addis Ababa.

4.4. Some Major Problems with Addis Ababa Water Supply

4.4.1. Lack of Water Supply

In Addis Ababa rapid urbanization is taking place. This includes higher population growth, the construction of new apartments and investment in the city. This rapid growth has led to an increasing demand for water from the original water treatment facility. The demand for domestic water is growing at a faster rate than the supply. Even though the Addis Ababa Water Supply and Sewerage Authority (AAWSA) is working to increase the supply capacity, it is currently not able to supply enough drinking water to the growing population. This has resulted in water shortages in many areas of the city. As a result, drinking water is now being supplied on a schedule. Unscheduled water supply disruptions are common in many parts of the city. It is not uncommon for tap water to be supplied only once per week in some parts of the city. This is worst for residents located at higher altitudes and those living in the higher floors of condominium apartments. This is due to the fact that there may be insufficient pressure in the system to supply the water to elevated areas unless a booster pump is used.

The combination of scheduled water supply and an aging, leaky distribution systems results in low pressures in the distribution network. This can result in the intrusion of external contaminants into the leaky and cross-connected infrastructure during supply interruption and reinstatement events.

4.4.2. Water Supply Disruption

In Addis Ababa, household drinking water quality deteriorates after treated water leaves the treatment plant and enters into the distribution system. A major factor causing this deterioration is the frequent supply interruptions which are common in most areas of Addis Ababa. The main reason for these disruptions is the lack of available water supply. This results in a drop in pipe water-pressure due to the topographic variation between the distribution zones and the supplying of available water on a scheduled basis. Water supply mains and service connections can also break during the construction of new infrastructure within the city. Power cuts are also common and contribute to the disruption of the water supply. During supply disruptions, the pressure inside the pipelines can fall and then allow intrusion of external contaminants from unhygienic areas where water supply pipes have been laid. Evidence of this has been found in the overall compliance assessment presented in Table 4.2. This data shows that almost all tap

water samples collected after a supply interruption and reinstatement event failed to comply with the appropriate drinking water standards.

4.4.3. Lack of an Integrated Water Supply Distribution System

Within the water supply distribution system, there are many interrelated factors that can affect the water quality. Some of these factors include: the pipelines age; corrosion of the supply infrastructure; leakage into the pipes; and the nature of the pipeline connection and its resilience to environmental factors such as weather. These factors, together with the surrounding sanitation conditions of the area, can adversely affect the quality of the drinking water supplied to households.

It has also been observed that the water supply distribution systems in most slum areas in Addis Ababa City are old, leaky and corroded. It is also common for the water supply system to be cross-connected with sewerage lines Addis Ababa (Figure 4.2).

Source: (Birhanu, 2007)

Figure 4.2: Water supply pipelines cross-connected with sewerage lines. Pipes are covered with solid liquid and wastes

There is no proper management of solid and liquid waste in Addis Ababa. Sewerage lines are often used for the disposal of wastes generated by the residents of the city (Figure 4.3). This also adversely affects the household drinking water quality of Addis Ababa.

Source: Photo taken from W-6

Figure 4.3: Drainage sites filled with liquid waste generated by household residents.

Many customers have complained of the water quality degradation within the city. This has resulted in the AAWSA putting in effort to replace the old metallic service connections with HDPE pipeline. However, most of these connections pass through old resident buildings and their foundations. Because of this, it is common to see service connections laid along drainage lines and exposed to the external environment (Figure 4.4). Partial pipeline replacements (HDPE + old metallic pipelines) can result in loose fittings and the loss of strength in the junctions (Figure 4.4). In addition, exposing the water supply distribution system to the external environment, such as fluctuation in temperature, can rapidly degrade the residual chlorine content of the water.

Figure 4.4: Water supply pipelines lay along drainage lines. These lines are exposed to the environment.

The factors mentioned here appear to be the major contributors to degradation of water quality in W-6 and the wider Bole subcity (Figure 4.5). As a result, the water collected from household taps often does not meet the Ethiopian drinking water standards (WHO) for the physical, chemical and microbiological water parameters tested (Table 4.2).

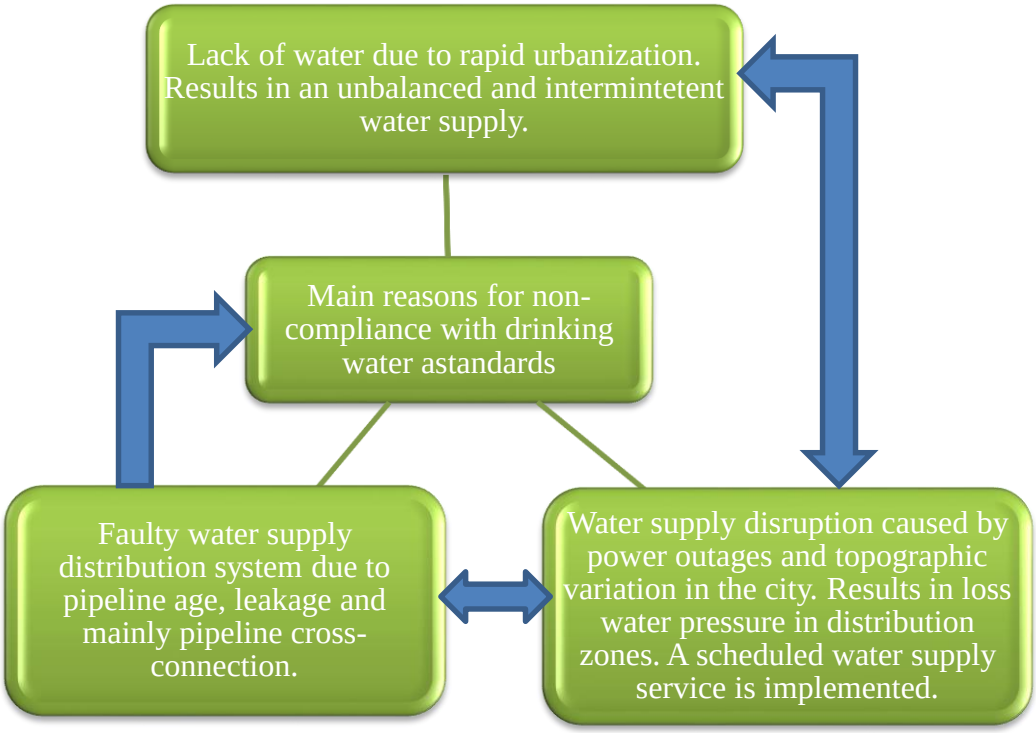


Figure 4.5: Summary of the main reasons why household drinking water is non-compliant with the drinking water standards in W-6 and the wider Bole subcity.

4.5. Remedial Actions Required in Addis Ababa City

There are many interconnected factors that affect the household drinking water quality in Addis Ababa. Because of this, there are many management options that can be recommended to minimise the deterioration of the water quality within the distribution system. Managing these issues individually can be both financially and technically infeasible. The following management options are suggested to reduce the degradation of water quality in the distribution systems.

4.5.1. Providing Enough Water

Ethiopia and Addis Ababa are gifted with a substantial quantity of surface and groundwater resources. Despite these substantial water resources, the main driving force for the deterioration of household drinking water is the lack of supply. This study indicates that even though there

are significant problems with the distribution system, a continuous supply would reduce the probability of contaminant intrusion caused by the drop in pipeline-pressure. Therefore, the entity for domestic water supply (AAWSA) should increase the capacity of their operations to supply enough drinking water to the residents of Addis Ababa residents.

The supply of water to industry and construction projects puts significant pressure on the water supply in Addis Ababa. This results in a scarcity of water to household users. As there is plentiful groundwater available within the shallow aquifers in the Addis Ababa area, allowing industries and construction works to develop and use their own private wells may assist in reducing the demand for surface water.

4.5.2. Improving Water Supply Distribution Systems

As summarised in Figure 4.6, there is a strong relationship between the condition of the water supply distribution system (pipelines age, corrosion, leakages and pipeline cross-connections) and the environment where the pipelines are laid (Figure 4.2 and Figure 4.3). In this study, it was observed that the condition of the pipes combined with unhygienic environments and intermittent water supply adversely affects the quality of household drinking water in W-6 and the wider Bole subcity of Addis Ababa. There is strong evidence for water quality deterioration and non-compliance with the drinking water standards. This is a result of the supply disruption and intrusion of contaminants. This was found in all tap water samples collected after supply interruption and reinstatement events.

The replacement of degraded water supply infrastructure and redesign of the distribution systems to avoid pipeline cross-connections would assist in improving water quality. Proper maintenance of the infrastructure would also assist in providing safe water to customers. The recommended remedial actions and their integration with factors that can improve water quality are summarised in Figure 4.6.

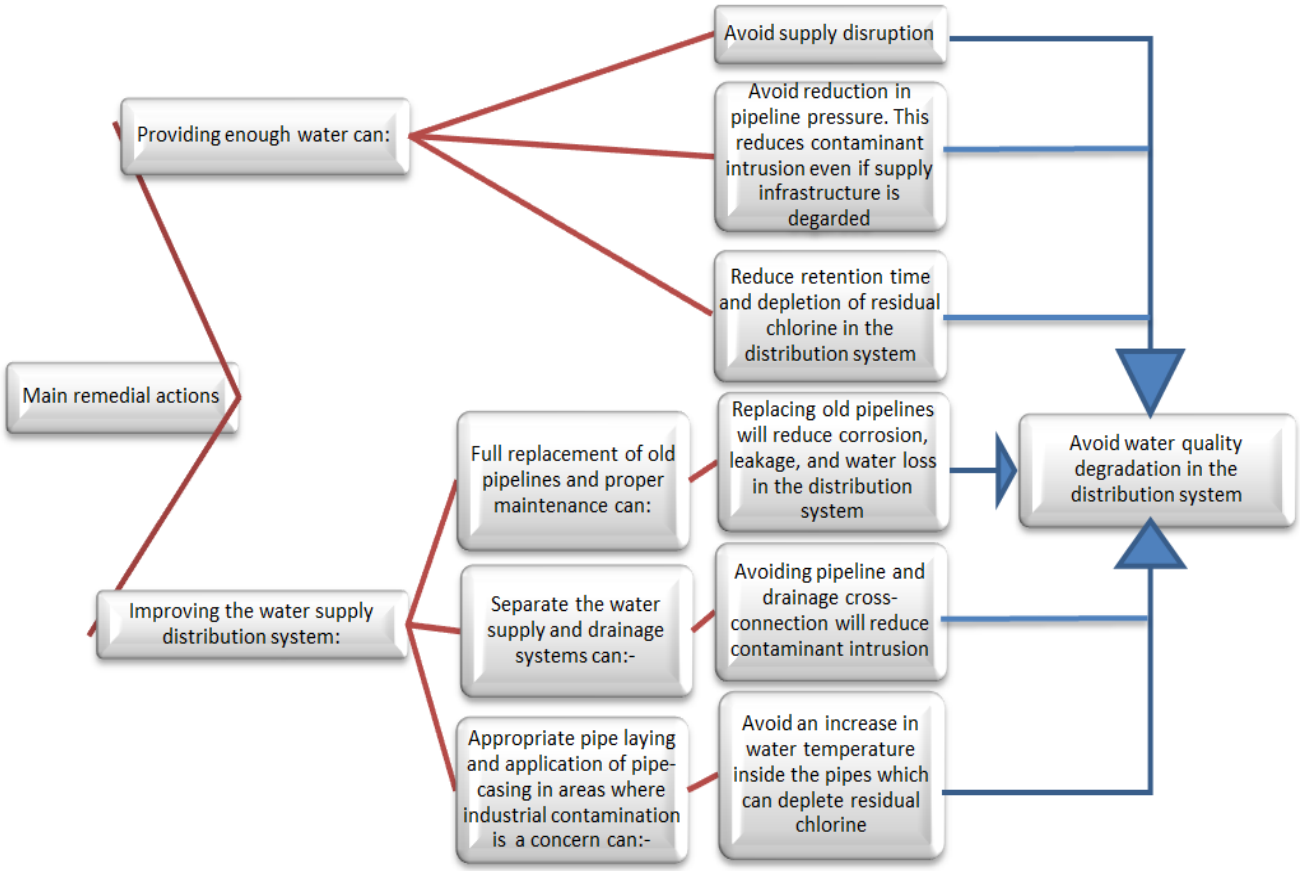


Figure 4.6: Diagram presenting possible remedial actions for the water supply in Addis Ababa, Ethiopia.

It was also observed that rapid depletion in residual chlorine concentrations occurs in the water after it has left the treatment plant and entered into the distribution system. In most household tap water samples collected far away from the LTP, residual chlorine concentrations were not maintained. Samples were found to have residual chlorine concentrations much lower than those recommended by the Ethiopian drinking water standards (WHO). In order to disinfect pathogens that may enter the distribution system, and to ensure that the water is safe to drink, the recommended residual chlorine concentration should be maintained throughout the distribution system. In order to do this, additional chlorination should be done at terminals and reservoirs within the city centre.

5. CONCLUSION AND RECOMMENDATION

Access to clean and safe drinking water is a fundamental human requirement. However, contaminated water can serve as a vector for disease transmission and cause acute and chronic human health problems unless it is deemed safe to drink. To prevent such illnesses, many technologies have been developed to treat, disinfect and supply safe drinking water quality. However, despite these advancements, water supply distribution systems can adversely affect the drinking water quality before it is delivered to consumers (Maksimović & Butler, 2005; Payment *et al.*, 2003). These issues are worst in developing countries like Ethiopia where water is supplied through old and degraded pipelines that often pass through unhygienic environments.

The primary aim of this research was to investigate the effect that water distribution systems may have on household drinking water quality in Christchurch New Zealand and Addis Ababa, Ethiopia. Water samples were collected from the distribution source and from household taps in both cities. The samples were then tested for various physical, chemical and biological water quality parameters. The data collected was used to determine if water samples complied with national drinking water quality standards in both countries. The following conclusions and recommendations have been determined from the data collected:

5.1. Effect of the Distribution System on Water Quality

5.1.1. In Christchurch City

- The differences in conductivity and turbidity values, and nitrate, nitrite and total zinc concentrations between the source and household tap water samples were not statistically significant.
- The differences in pH and total iron concentration between the source and household tap water samples in Christchurch were significantly different.
- The pH values were found to be lower in the household tap water samples. It is possible that corrosion of the different materials (asbestos cement, cast iron and galvanised steel) may be occurring in the distribution system.
- It was thought that corrosion in the distribution system would result in higher iron concentrations in the household tap water samples. However, the mean total iron

concentration was higher in the source water. The greatest total iron concentration values were from the 2011 water quality monitoring data adopted from the CCC. A possible explanation for this increase in total iron concentration in the source water may be due to damage to the wells and pump stations during the 2011 earthquake events.

- Neither *E. coli* nor faecal coliform bacteria were detected in either the source or household tap waters. This confirms that drinking water is delivered safely without any bacterial contamination in the water supply distribution system.
- A compliance assessment with New Zealand drinking water quality standards was completed. A number of samples did not comply for turbidity and total iron concentrations in the source water. This may be attributed to the 2011 earthquake event. Non-compliance in pH occurred in both the source and tap waters. The possible reason for the lower pH level in the tap waters may be due to corrosion of the different pipe materials as noted earlier. All other measurements for the physiochemical parameters (conductivity, turbidity, nitrate, nitrite and total zinc concentrations) and microbiological parameters (*E. coli* and faecal coliform bacteria) tested were found to comply with drinking water quality standards.
- Based on the results obtained from this study, it is concluded that water quality is not degraded in Christchurch City's water supply distribution system. The water supply distribution system delivers the city's renowned natural water to the consumers without compromising its natural quality.

5.1.2. In Addis Ababa City

- The pH and turbidity values, and nitrate and nitrite concentrations measured between the source water (LTP) and household tap water samples collected in W-8, W-6 and the wider Bole subcity (B.S) were found to not be statistically significant. However, the pH levels measured in the household tap waters were lower than the source water. Higher turbidity values were also measured household tap water samples collected in remote areas.
- The conductivity values, and total zinc, total iron and residual chlorine concentrations measured in the source water (LTP) and samples collected from household taps from W-8, W-6 and the wider Bole subcity (B.S) were significantly different. This suggests that the household drinking water quality has deteriorated after the treated water leaves the treatment plant and enters into the water supply distribution system.

- The conductivity and turbidity values and residual chlorine concentrations measured in samples collected from W-8 and W-6 were significantly different. These differences suggest that water collected from more remote houses (W-6) is vulnerable to contamination in the distribution system. However, the differences in total zinc and total iron concentrations were not statistically significant. This suggests that corrosion is still taking place in the recently constructed distribution infrastructure of W-8.
- Elevated conductivity and turbidity values, total zinc and iron concentrations, and *E. coli* and total coliform concentrations were measured in samples collected from households in remote locations after supply interruption and reinstatement events. These samples were collected from households in W-6 and the wider Bole subcity (B.S). Results were also reported as outliers.
- There was a strong correlation between the distance from the LTP where samples were gathered and the concentration of residual chlorine. Households located far away from the LTP were found to have little or no residual chlorine in their tap water. As residual chlorine concentrations were depleted, greater concentrations of *E. coli* and total coliform bacteria were detected in tap water samples collected from households located in distant proximity to the LTP. These areas often had old, degraded and cross-connected pipelines laid through unhygienic environments.
- A compliance assessment with the Ethiopian (WHO) drinking water standards was conducted. All water samples collected from the LTP were found to comply with the drinking water standards. However, a number of samples collected from household taps were found to have pH or turbidity values, or total iron and residual chlorine concentrations which were non-compliant with the drinking water standards.
- Neither *E. coli* nor total coliform bacteria were detected in water samples collected from the LTP. This indicates that the drinking water produced is safe to be consumed at this site. However, *E. coli* and total coliform bacteria were detected in household tap water samples. The number of non-compliant samples increased in samples collected from household taps in remote areas of W-6 and the wider Bole subcity (B.S). These areas often have an intermittent supply water supply as well as an old, degraded and cross-connected water supply distribution system.
- The main cause of water quality degradation in the distribution system in W-6 and the wider Bole subcity (B.S) is likely due to the water supply disruption. This results in the intrusion of external contaminants through the leaky and cross-connected pipelines of the distribution

system. This may ultimately result in non-compliance with the Ethiopian (WHO) drinking water standards.

- Tap water samples collected after supply interruption and reinstatement events were found to have elevated conductivity and turbidity values and total zinc, total iron, *E. coli* and total coliform concentrations. Residual chlorine concentrations in these samples were often below detection limits.
- Based on the results from this study, it is concluded that the combination of an old, degraded and cross-connected distribution system with water supply disruptions resulted in the degradation of the drinking water quality in Addis Ababa.

5.2. Recommendations for Further Research and Improvements

5.2.1. For Christchurch City

- In the data used for the source and tap waters, there was lack of time-match in sampling dates, and the samples were also analysed using different instruments. Therefore, water samples from the source and household taps should be collected at the same time, and should also be analysed using the same laboratory instruments. This will minimise instrumental variations and any possible errors. Water samples analysed with different laboratory instruments may not give consistent and comparable results.

5.2.2. For Addis Ababa City

Recommendations for organizations providing the drinking water include;

- The times in which water are supplied to some households is uncertain. During supply disruption, households put out containers and leave their faucets open. The containers fill when the supply resumes. During this time, it is common to hear the sucking of air from the faucet which indicated a negative pressure in the system. This effect enhances the intrusion of contaminants into old, degraded and leaky pipelines. The water supply entity should ensure customers flush their taps of any contaminated water when the water supply resumes.
- Technicians and contractors working on the water supply infrastructure should be trained and monitored to ensure pipeline cross-connections are avoided.
- Water supply customers should be instructed to not leave their faucets open during supply disruption events. Back flow prevention valves could also be installed stabilize pipeline-pressure fluctuations during supply disruption and prevent any contaminant intrusion.
- Supplementary chlorination of the water supply in remote areas would reduce the microbial contamination of water in households far away from the LTP.
- Investment in the water supply infrastructure is required to avoid supply disruption events. This is a major cause of water quality degradation in Addis Ababa.
- An integrated water quality monitoring program and a robust water quality monitoring database is needed in the Addis Ababa Water and Sewerage Authority (AAWSA) laboratory. Monitoring data could be recorded in spreadsheet form which would allow for the identification of trends in water quality. This data could be used to design remedial actions that may be required.

Recommendations for further research;

- Water supply disruption leads to water quality degradation in the distribution system. The effect of this on household tap water quality may be worst for the slum dwellers in remote areas of the city. A study on other slum areas could be helpful to assist in the implementation of a targeted management option.
- It was observed that a supply disruption event was causing residents to store water in elevated storage tanks, barrels and other plastic containers. These were often handled very

poorly, especially in slum areas. Contamination of this water by bacteria and other chemicals is probable. Therefore, further research, community engagement and household awareness in hygiene practice is required to fix this effect.

- There is a need to further investigate the mechanisms by which the intermittent water supply affects the water quality and the distribution system itself.
- The surface water that supplies Addis Ababa with drinking water originates from areas where intensive agricultural farms are located. Farmers in these areas apply a variety of pesticides and herbicides to the land. These chemicals could cause chronic health problems. There is therefore a need to investigate the fate of these chemicals and whether the treatment plants are capable of effectively removing these chemicals from the water supply.
- Most of the scattered wells used to source drinking water in Addis Ababa are located on the sides of rivers. Uncontrolled waste disposal and leaching into ground water may affect the quality of these water supplies. A comprehensive assessment is required to examine this possibility.

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APPENDICES

Appendix A: Raw water quality data for physical, chemical and microbiological parameters measured in tap water samples collected from Christchurch City.

Parameters									
Pump Stations Name	Physical			Chemical				Microbiological	
	pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	E. coli	FC
		µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
	7.09	117.0	0.80	6.188	0.0132	0.0023	0.02	0	0
	7.14	115.2	0.73	7.072	0.0066	0.0136	0.02	0	0
Picton	7.42	116.4	0.86	6.188	0.0132	0.0109	0.02	0	0
	7.25	121.5	0.49	7.072	0.0363	0.0038	0.02	0	0
	6.99	139.0	0.51	7.072	0.0132	0.0290	0.02	0	0
Jeffreys	6.65	118.7	0.28	5.746	0.0165	0.0113	0.02	0	0
	7.04	133.0	0.38	5.304	0.0198	0.0197	0.03	0	0
	7.34	125.0	0.44	2.210	0.0561	0.0136	0.02	0	0
Auburn	6.99	142.0	0.31	8.398	0.0066	0.2000	0.02	0	0
	7.19	192.8	0.21	7.514	0.0528	0.0270	0.02	0	0
Main	6.95	221.0	0.63	6.630	0.0330	0.0320	0.02	0	0
Pump	7.05	191.3	0.64	11.934	0.0462	0.0240	0.02	0	0
	6.53	134.6	0.90	7.072	0.0594	0.0580	0.02	0	0
	6.86	134.8	0.85	7.514	0.0462	0.0290	0.03	0	0
Avonhead	6.87	135.0	0.65	7.956	0.0561	0.0200	0.02	0	0
	7.56	106.4	0.55	4.862	0.0561	0.0059	0.04	0	0
	7.52	100.4	0.75	4.420	0.0495	0.0195	0.02	0	0
Tara	7.58	100.6	0.63	4.420	0.0462	0.0340	0.03	0	0
	7.71	132.5	0.56	2.873	0.0198	0.0176	0.02	0	0
	7.8	124.1	0.95	1.989	0.0396	0.0100	0.02	0	0
Wrights	7.77	143.2	0.45	5.304	0.0330	0.0162	0.05	0	0
	7.88	131.2	0.80	5.304	0.0132	0.0520	0.05	0	0
	7.76	133.4	0.54	3.536	0.0132	0.0129	0.03	0	0
Sydenham	7.71	132.6	0.85	4.862	0.0198	0.0260	0.03	0	0
	7.98	117.3	0.64	4.420	0.0462	0.0047	0.03	0	0
	8.06	117.1	0.74	5.304	0.0132	0.0087	0.02	0	0
Addington	7.98	117.3	0.58	5.746	0.0528	0.0069	0.03	0	0

Appendix B: Raw water quality data for physical, chemical and microbiological parameters measured in the source water samples collected in Christchurch City. Data was obtained from the CCC (from 2010 - 2014). Note: Results highlighted with yellow colour are the greatest values found in the 2011 monitoring data.

Parameters									
Pump Stations Name	Physical			Chemical				Microbiological	
	pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	E. coli	FC
		µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
	6.90	87.0	3.30	0.265	0.017	0.001	1.200	0	0
	8.25	93.2	9.50	0.398	0.096	0.005	1.340	0	0
Picton	7.90	114.0	0.13	1.039	0.083	0.003	0.003	0	0
	7.70	100.0	0.14	0.676	0.023	0.002	0.010	0	0
	8.00	123.0	0.14	0.676	0.023	0.002	0.010	0	0
Jeffreys	7.70	106.0	0.06	1.238	0.083	0.002	0.002	0	0
	7.10	133.0	3.40	0.619	0.017	0.029	0.086	0	0
	7.20	127.0	5.55	3.779	0.033	0.020	0.450	0	0
Auburn	8.15	126.5	0.33	3.691	0.120	0.008	0.077	0	0
	7.10	187.0	0.10	7.956	0.017	0.007	0.002	0	0
	7.40	196.0	0.10	5.370	0.033	0.002	0.005	0	0
Main Pump	7.00	212.0	0.10	8.707	0.033	0.002	0.003	0	0
	7.05	140.5	0.15	8.354	0.033	0.032	0.004	0	0
	7.95	133.0	0.18	1.193	0.033	0.004	0.014	0	0
Avonhead	7.20	135.0	0.10	7.514	0.033	0.019	0.002	0	0
	7.90	135.0	0.10	0.884	0.033	0.002	0.010	0	0
	7.90	135.0	0.30	0.796	0.033	0.004	0.031	0	0
Tara	7.90	135.0	0.11	0.840	0.185	0.002	0.002	0	0
	6.90	323.0	0.25	28.730	0.033	0.036	0.007	0	0
Wrights	7.00	154.0	0.80	4.111	0.033	0.086	0.024	0	0
	7.85	142.0	8.42	0.433	0.017	0.002	0.565	0	0
	7.80	123.0	0.10	1.414	0.033	0.002	0.002	0	0
Sydenham	7.95	122.5	0.30	1.127	0.040	0.002	0.040	0	0
	8.00	113.0	0.10	1.547	0.033	0.002	0.002	0	0
	8.10	114.0	5.30	1.591	0.033	0.027	0.630	0	0
Addington	8.00	115.0	0.10	2.210	0.033	0.020	0.009	0	0

Appendix C: Raw water quality data for physical, chemical and microbiological parameters measured in the source water samples collected from the LTP in Addis Ababa City.

Parameters									
Physical			Chemical					Microbiological	
pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	RC	E.coli	TC
	µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
6.6	146.5	2.50	17.16	0.01584	1.26	0.039	0.80	0	0
6.76	132.4	1.15	33.00	0.01947	1.16	0.036	0.90	0	0
7.36	110.6	0.58	19.80	0.02079	1.13	0.029	0.80	0	0
7.32	109.8	0.43	21.12	0.02442	1.11	0.023	0.80	0	0

Appendix D: Raw water quality data for physical, chemical and microbiological parameters measured in the tap water samples collected from W-8 in Addis Ababa City.

Parameters									
Physical			Chemical					Microbiological	
pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	RC	E.coli	TC
	µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
6.76	139.0	0.78	15.62	0.0188	1.34	0.190	0.35	0	0
6.73	124.3	0.72	20.90	0.0175	1.42	0.084	0.40	2	29
7.26	110.5	0.58	24.20	0.0158	1.46	0.177	0.50	0	0
7.36	112.6	0.79	23.32	0.0155	1.35	0.085	0.45	0	4
6.46	137.4	0.65	19.80	0.0102	1.21	0.006	0.45	0	0
6.59	128.8	0.65	16.28	0.0158	1.33	0.045	0.40	0	0
7.24	110.1	0.59	23.76	0.0399	1.19	0.047	0.60	0	0
7.29	101.2	0.58	22.88	0.0162	1.45	0.058	0.50	0	0
6.76	147.5	1.89	17.82	0.0320	1.21	0.298	0.30	0	0
6.76	124.4	1.20	17.16	0.0162	1.43	0.161	0.50	0	0
7.11	115.4	2.01	21.12	0.0158	1.58	0.643	0.45	0	12
7.25	114.5	0.96	19.80	0.0152	1.36	0.735	0.45	0	0
6.83	137.0	0.63	22.00	0.0211	1.40	0.029	0.40	0	0
6.71	123.2	0.65	22.00	0.0195	1.18	0.021	0.50	1	40
7.22	109.2	0.65	23.76	0.0165	1.31	0.026	0.50	0	0
7.24	108.7	0.85	22.44	0.0168	1.37	0.031	0.65	0	0
6.70	137.1	0.61	20.24	0.0211	1.46	0.041	0.50	0	0
6.69	124.1	0.55	22.00	0.0198	1.18	0.092	0.40	0	0
7.21	110.3	0.75	21.12	0.0139	1.32	0.058	0.50	0	0
7.17	109.9	0.65	22.00	0.0149	1.34	0.035	0.55	0	0

Appendix E: Raw water quality data for physical, chemical and microbiological parameters measured in the tap water samples collected from W-6 in Addis Ababa City.

Parameters									
Physical			Chemical					Microbiological	
pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	RC	E.coli	TC
	µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
6.76	154.9	0.85	19.58	0.0152	1.46	0.135	0.30	2	4
6.46	150.9	1.01	30.80	0.0125	1.26	0.108	0.15	4	25
7.22	126.7	3.00	31.68	0.0142	1.45	0.101	0.00	0	0
7.21	119.9	0.89	23.32	0.0116	1.23	0.080	0.15	0	0
6.66	161.5	0.80	22.00	0.0086	1.41	0.066	0.20	0	4
6.66	138.0	0.78	23.76	0.0234	1.48	0.058	0.00	33	144
7.42	127.3	9.30	17.16	0.0116	1.32	0.068	0.00	0	4
7.01	131.1	0.85	17.60	0.0125	1.21	0.028	0.10	0	0
6.76	158.6	1.30	22.00	0.0079	1.38	0.079	0.30	0	0
6.66	143.5	1.10	25.08	0.0069	1.33	0.093	0.00	4	8
7.00	124.1	6.57	18.04	0.0083	1.35	0.538	0.00	0	0
7.32	121.5	5.37	29.48	0.0149	1.34	0.146	0.25	0	0
6.76	165.5	1.10	22.00	0.0195	1.49	0.072	0.15	0	0
6.66	138.4	0.85	22.88	0.0191	1.47	0.048	0.20	0	0
6.76	132.9	1.50	21.12	0.0248	1.44	0.458	0.00	3	7
7.25	127.7	1.01	21.12	0.0152	1.26	0.386	0.15	0	0
6.76	140.6	1.01	20.68	0.0257	1.29	0.036	0.10	0	0
6.66	133.6	0.99	28.16	0.0215	1.48	0.060	0.10	3	17
7.32	121.9	3.21	17.60	0.0125	1.33	0.069	0.00	2	11
7.27	115.4	1.03	21.56	0.0188	1.47	0.047	0.25	0	0

Appendix F: Raw water quality data for physical, chemical and microbiological parameters measured in the tap water samples collected from the wider Bole subcity (B.S) in Addis Ababa City.

Parameters									
Physical			Chemical					Microbiological	
pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	RC	E.coli	TC
	µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
6.99	146.5	0.55	20.68	0.01947	1.24	0.039	0.50	0	0
6.89	147.0	1.55	20.24	0.02046	1.34	0.051	0.40	3	9
6.76	173.3	1.15	26.40	0.02145	1.47	0.252	0.00	0	0
6.66	147.2	0.80	19.36	0.02145	1.43	0.067	0.60	0	1

Appendix F: Continued

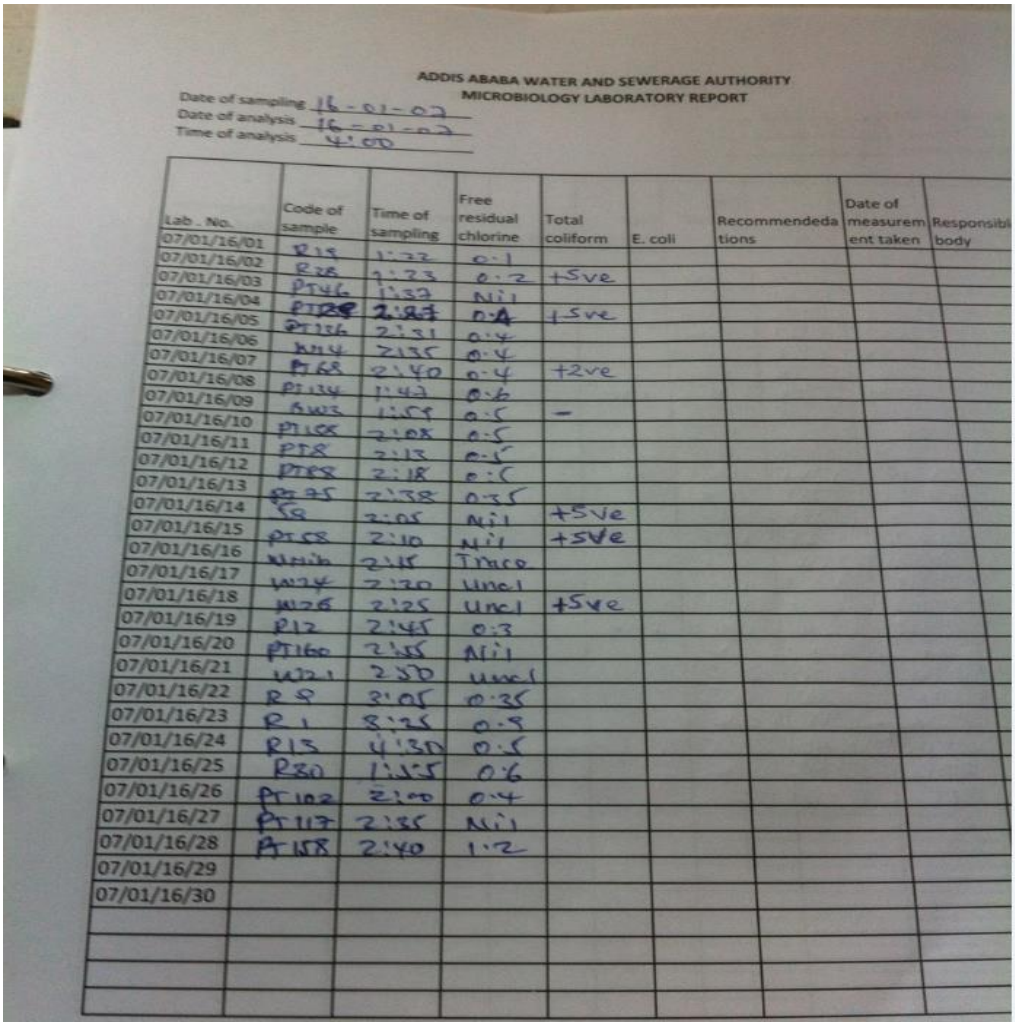
6.69	178.3	3.22	20.68	0.02244	1.44	0.182	0.15	0	14
6.46	151.0	0.65	21.56	0.00891	1.32	0.082	0.10	17	56
6.77	155.0	7.20	23.32	0.01947	1.45	0.135	0.20	2	9
7.19	113.3	0.87	22.44	0.01419	1.24	0.047	0.15	0	0
7.24	112.0	1.18	33.44	0.01716	1.36	0.146	0.25	0	0
7.16	113.3	2.66	22.44	0.01485	1.31	0.047	0.00	32	71
7.15	120.6	2.95	25.96	0.01782	1.19	0.069	0.00	0	0
7.16	131.5	0.84	22.44	0.01716	1.39	0.077	0.20	0	0
7.26	127.9	0.70	25.08	0.01914	1.42	0.071	0.15	4	21
7.16	108.9	0.65	23.76	0.02145	1.43	0.064	0.10	0	8
7.21	111.9	0.92	24.64	0.02112	1.39	0.063	0.10	2	10
7.22	108.9	0.83	22.88	0.02244	1.21	0.041	0.15	0	0
7.46	106.4	0.78	18.92	0.01386	1.21	0.021	0.00	0	0
7.41	108.0	0.55	19.36	0.01221	1.23	0.012	0.00	8	23
7.42	108.2	0.71	18.48	0.01287	1.42	0.06	0.15	7	16
7.37	109.0	0.75	16.72	0.01452	1.34	0.073	0.00	0	0

Appendix G: Raw data for a number of physical and chemical water quality parameters analysed after customers reported discoloured and turbid waters coming from their taps in Addis Ababa.

Parameters									
Physical			Chemical					Microbiological	
pH	Conductivity	Turbidity	Nitrate	Nitrite	Zinc	Iron	RC	E.coli	TC
	µS/cm	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100ml	CFU/100ml
6.46	182.9	22.0	33.44	0.01452	N/T	0.108	0	N/T	N/T
6.71	136.9	16.0	31.68	0.01419	N/T	0.101	0	N/T	N/T
7.36	255.9	53.0	60.72	0.07491	N/T	1.312	0	N/T	N/T
7.48	571.9	15.5	13.20	0.02178	N/T	0.202	0	N/T	N/T
6.64	125.5	23.2	12.32	0.02013	N/T	0.164	0	N/T	N/T

Note: N/T- Not tested. These parameters were not tested due to prohibitive analytical costs.

Appendix H: Supplementary raw data for residual chlorine, E. coli and total coliform bacteria routinely monitored by AAWSA laboratory, Addis Ababa.



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

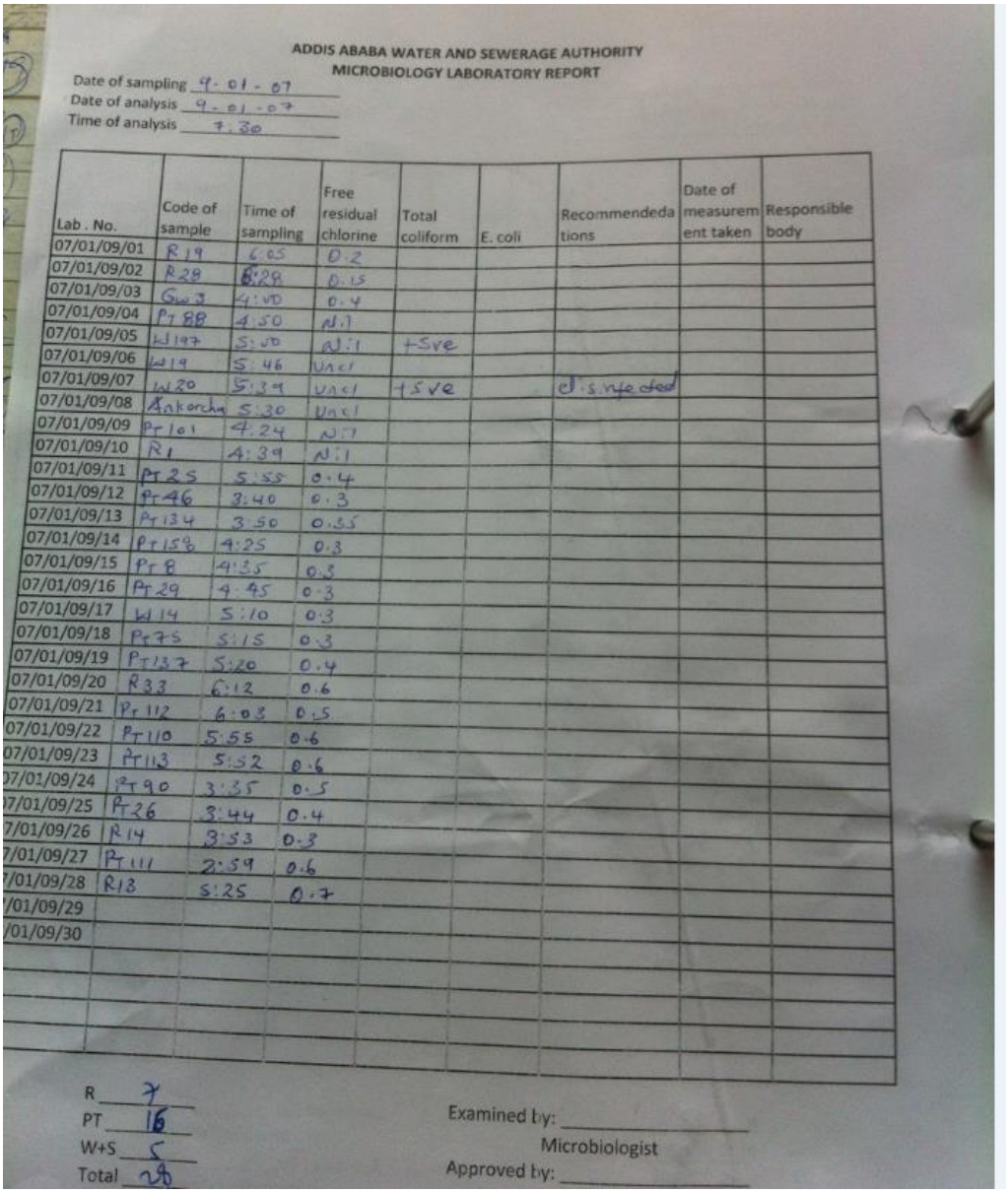
Date of sampling 16-01-07
Date of analysis 16-01-07
Time of analysis 4:00

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsibl body
07/01/16/01	R19	1:32	0·1					
07/01/16/02	R26	1:33	0·2	+5ve				
07/01/16/03	PT46	1:37	Nil					
07/01/16/04	PT89	2:27	0·4	+5ve				
07/01/16/05	PT136	2:31	0·4					
07/01/16/06	KN4	2:35	0·4					
07/01/16/07	PT68	2:40	0·4	+2ve				
07/01/16/08	PT134	1:43	0·6					
07/01/16/09	KW3	1:54	0·5	-				
07/01/16/10	PT108	2:05	0·5					
07/01/16/11	PT8	2:13	0·5					
07/01/16/12	PT85	2:18	0·5					
07/01/16/13	PT95	2:38	0·35					
07/01/16/14	R9	2:05	Nil	+5ve				
07/01/16/15	PT108	2:10	Nil	+5ve				
07/01/16/16	KW16	2:15	Trace					
07/01/16/17	W24	2:20	Uncl					
07/01/16/18	W26	2:25	Uncl	+5ve				
07/01/16/19	R12	2:45	0·3					
07/01/16/20	PT160	2:55	Nil					
07/01/16/21	W21	2:50	Uncl					
07/01/16/22	R9	3:05	0·35					
07/01/16/23	R1	8:25	0·9					
07/01/16/24	R13	4:30	0·5					
07/01/16/25	R80	1:35	0·6					
07/01/16/26	PT102	2:00	0·4					
07/01/16/27	PT117	2:35	Nil					
07/01/16/28	PT158	2:40	1·2					
07/01/16/29								
07/01/16/30								

ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 14/01/07
Date of analysis 14/01/07
Time of analysis _____

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendedations	Date of measurement taken	Re bo
07/01/14/01	PT 25	3:50	0.7					
07/01/14/02	PT 5	3:55	0.3					
07/01/14/03	PT 60	4:10	0.7					
07/01/14/04	PT 9	4:30	Trace					
07/01/14/05	PT 23	5:05	0.25					
07/01/14/06	R6	5:50	0.3					
07/01/14/07	PT 45	4:00	0.35					
07/01/14/08	PT 55	4:45	0.35					
07/01/14/09	R5	4:45	0.35					
07/01/14/10	R4	4:55	0.35					
07/01/14/11	R1	5:45	0.6					
07/01/14/12	PT 23	6:05	0.35					
07/01/14/13	W25	5:48	Uncl					
07/01/14/14	PT43	5:56	0.3					
07/01/14/15	PT83	6:00	Nil					
07/01/14/16	S10	6:05	Nil	+4	-Ve			
07/01/14/17	W4	6:15	Uncl	+4	-Ve			
07/01/14/18	WSucc	6:20	Uncl					
07/01/14/19	W13	6:25	Uncl	+2	-Ve			
07/01/14/20	R17	6:54	0.5					
07/01/14/21	PT53	7:04	0.3					
07/01/14/22	PT31	7:15	0.5					
07/01/14/23	R13	7:41	0.7					
07/01/14/24								
7/01/14/25								
7/01/14/26								
7/01/14/27								
7/01/14/28								
7/01/14/29								



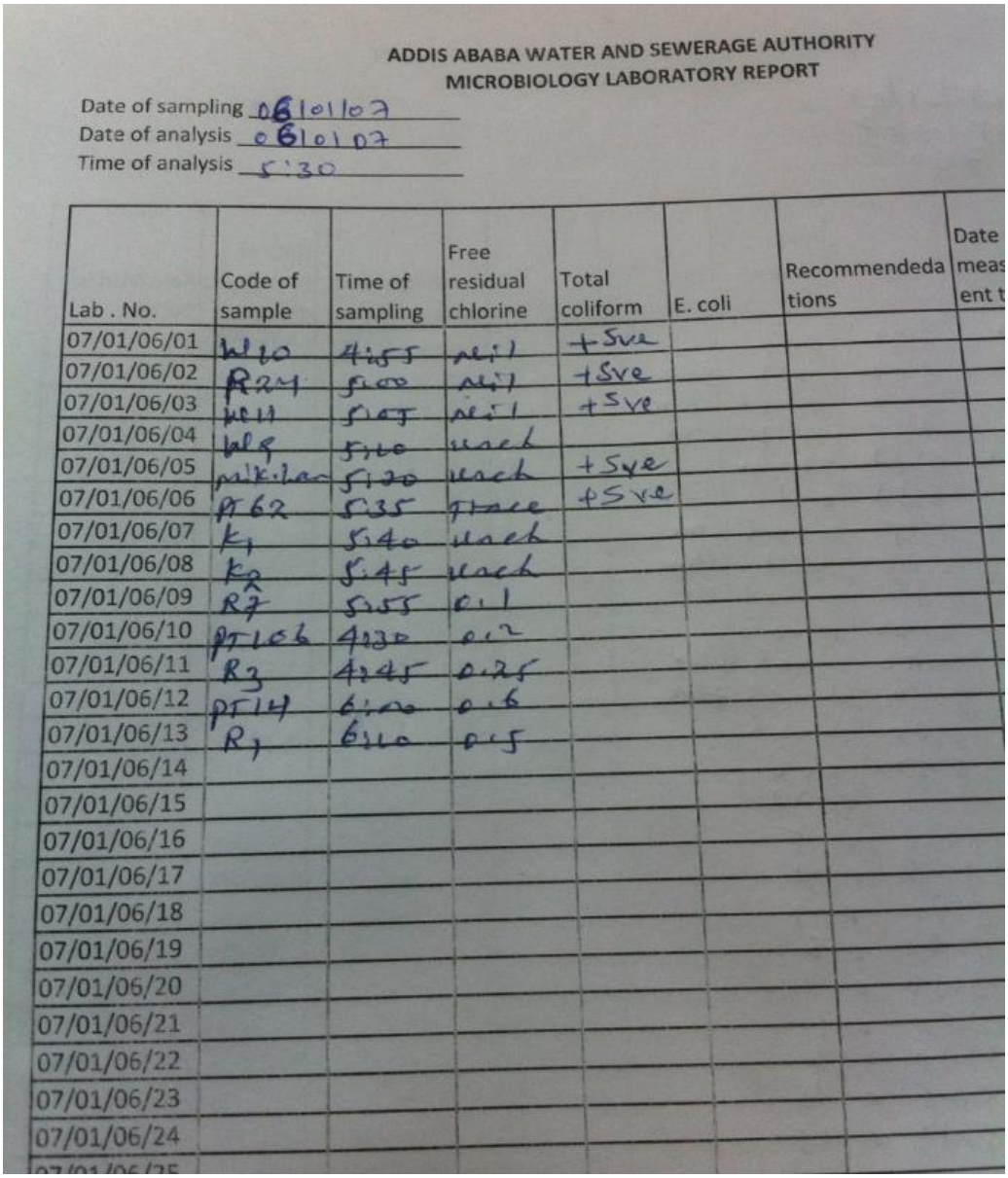
ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 9-01-07
Date of analysis 9-01-07
Time of analysis 7:30

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
07/01/09/01	R19	6:05	0.2					
07/01/09/02	R28	6:28	0.15					
07/01/09/03	Gw3	4:00	0.4					
07/01/09/04	Pt88	4:50	Nil					
07/01/09/05	W197	5:00	Nil	+Sve				
07/01/09/06	W19	5:46	Uncl					
07/01/09/07	W20	5:39	Uncl	+Sve		cl.s nfected		
07/01/09/08	Ankorcha	5:30	Uncl					
07/01/09/09	Pt101	4:24	Nil					
07/01/09/10	R1	4:39	Nil					
07/01/09/11	Pt25	5:55	0.4					
07/01/09/12	Pt46	3:40	0.3					
07/01/09/13	Pt134	3:50	0.35					
07/01/09/14	Pt158	4:25	0.3					
07/01/09/15	Pt8	4:35	0.3					
07/01/09/16	Pt29	4:45	0.3					
07/01/09/17	W14	5:10	0.3					
07/01/09/18	Pt75	5:15	0.3					
07/01/09/19	Pt137	5:20	0.4					
07/01/09/20	R33	6:12	0.6					
07/01/09/21	Pt112	6:03	0.5					
07/01/09/22	Pt110	5:55	0.6					
07/01/09/23	Pt113	5:52	0.6					
07/01/09/24	Pt90	3:35	0.5					
7/01/09/25	Pt26	3:44	0.4					
7/01/09/26	R14	3:53	0.3					
7/01/09/27	Pt111	2:59	0.6					
7/01/09/28	R13	5:25	0.7					
/01/09/29								
/01/09/30								

R 7
PT 16
W+S 5
Total 28

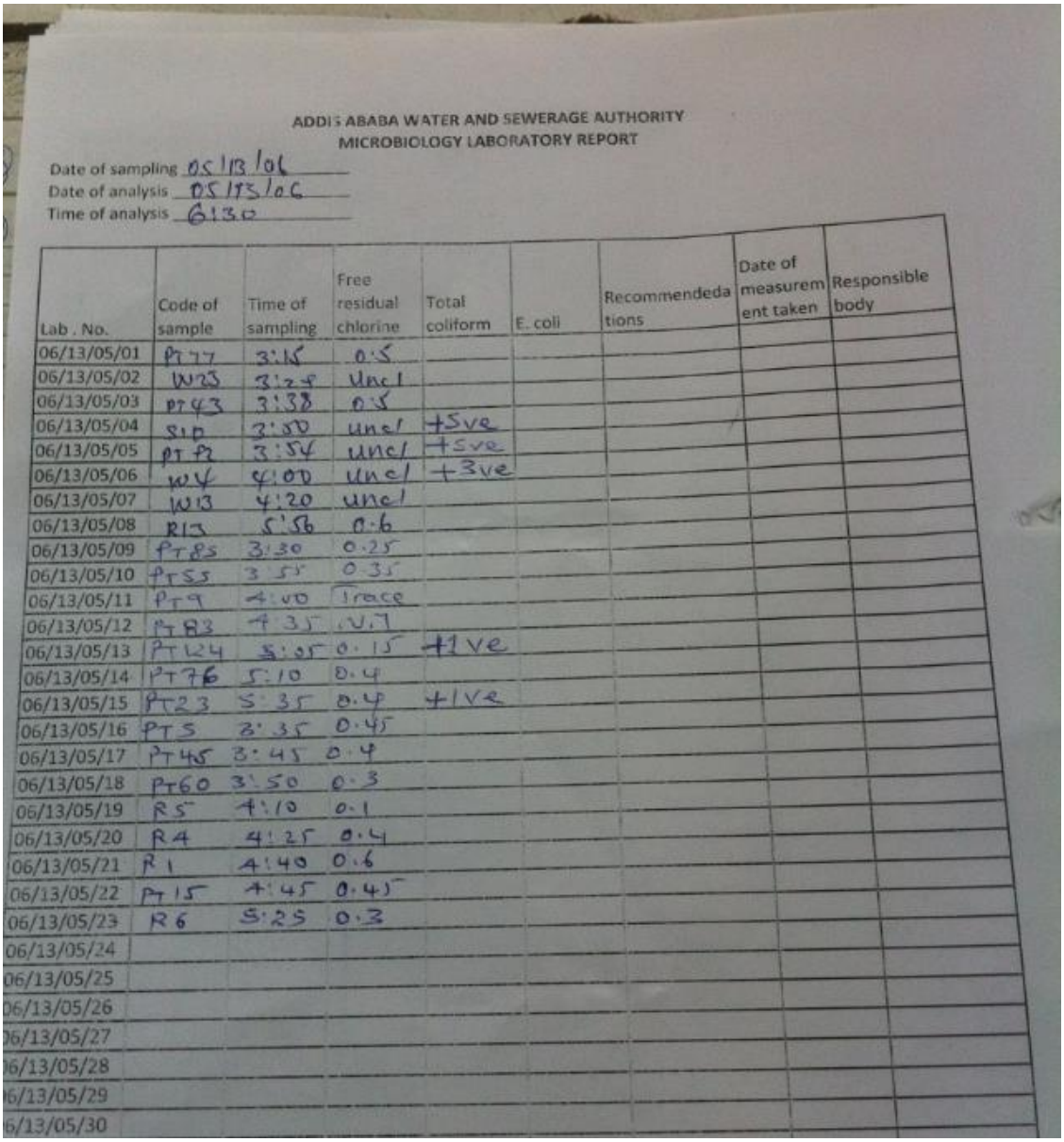
Examined by: _____
Microbiologist
Approved by: _____



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 06/01/07
Date of analysis 06/01/07
Time of analysis 5:30

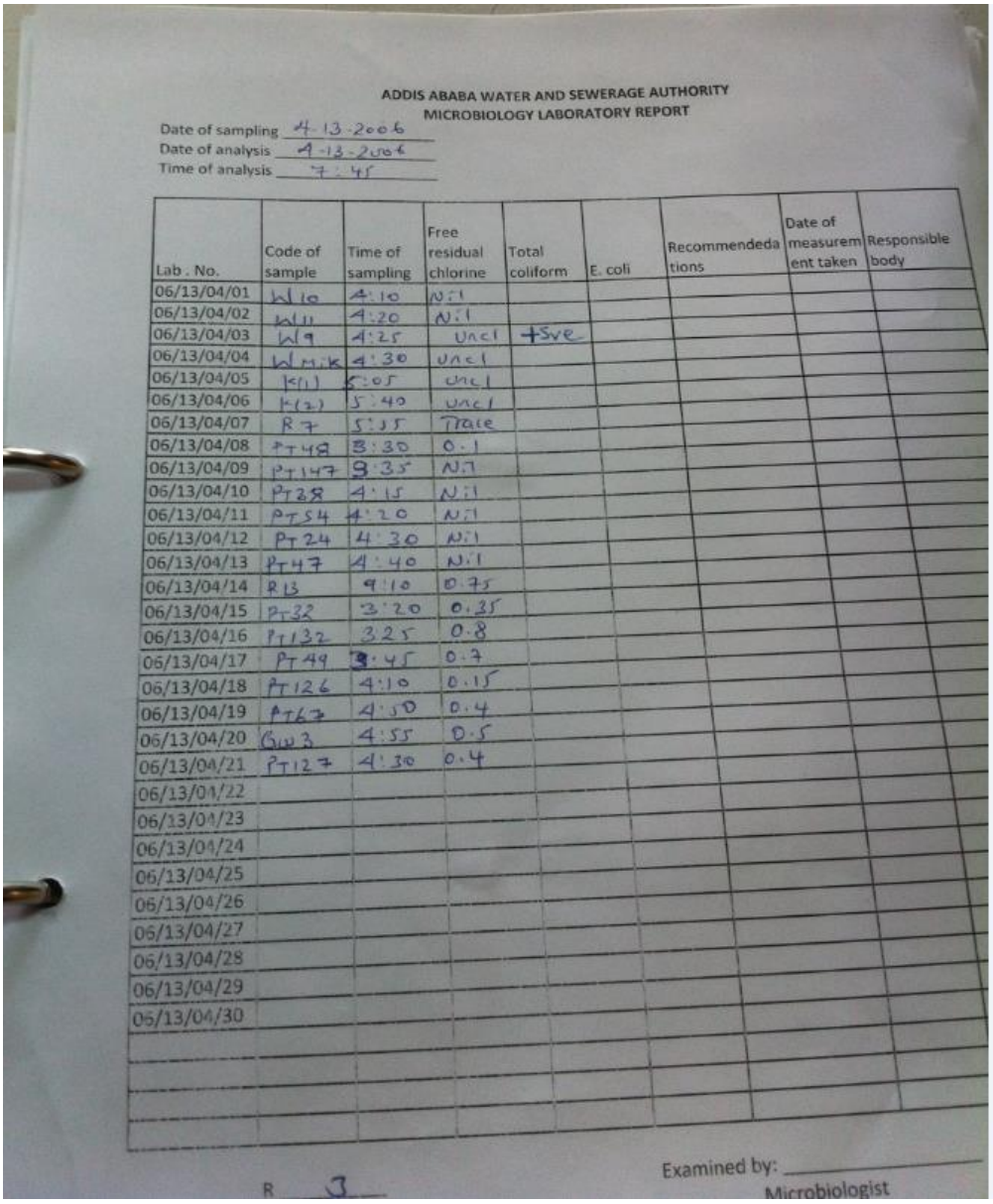
Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendedations	Date measent t
07/01/06/01	W10	4:55	Nil	+Sve			
07/01/06/02	R24	5:00	Nil	+Sve			
07/01/06/03	W11	5:07	Nil	+Sve			
07/01/06/04	W8	5:10	Nil				
07/01/06/05	Mikiso	5:20	Nil	+Sve			
07/01/06/06	PT62	5:35	Trace	+Sve			
07/01/06/07	K1	5:40	Nil				
07/01/06/08	K2	5:45	Nil				
07/01/06/09	R7	5:55	0.1				
07/01/06/10	PT106	4:30	0.2				
07/01/06/11	R3	4:45	0.25				
07/01/06/12	PT14	6:00	0.6				
07/01/06/13	R1	6:10	0.5				
07/01/06/14							
07/01/06/15							
07/01/06/16							
07/01/06/17							
07/01/06/18							
07/01/06/19							
07/01/06/20							
07/01/06/21							
07/01/06/22							
07/01/06/23							
07/01/06/24							
07/01/06/25							



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 05/13/06
Date of analysis 05/13/06
Time of analysis 6:30

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendedations	Date of measurement taken	Responsible body
06/13/05/01	PT77	3:15	0.5					
06/13/05/02	W33	3:24	Uncl					
06/13/05/03	PT43	3:38	0.5					
06/13/05/04	SID	3:50	uncl	+5ve				
06/13/05/05	PT P2	3:54	uncl	+5ve				
06/13/05/06	W4	4:00	Uncl	+3ve				
06/13/05/07	W13	4:20	uncl					
06/13/05/08	R13	5'56	0.6					
06/13/05/09	PT85	3:30	0.25					
06/13/05/10	PT55	3 55	0.35					
06/13/05/11	PT9	4:00	Trace					
06/13/05/12	PT83	4 35	0.7					
06/13/05/13	PT24	5:05	0.15	+1ve				
06/13/05/14	PT76	5:10	0.4					
06/13/05/15	PT23	5 35	0.4	+1ve				
06/13/05/16	PT5	3 35	0.45					
06/13/05/17	PT45	3:45	0.4					
06/13/05/18	PT60	3:50	0.3					
06/13/05/19	R5	4:10	0.1					
06/13/05/20	R4	4:25	0.4					
06/13/05/21	R1	4:40	0.6					
06/13/05/22	PT15	4:45	0.45					
06/13/05/23	R6	5:25	0.3					
06/13/05/24								
06/13/05/25								
06/13/05/26								
06/13/05/27								
06/13/05/28								
06/13/05/29								
06/13/05/30								



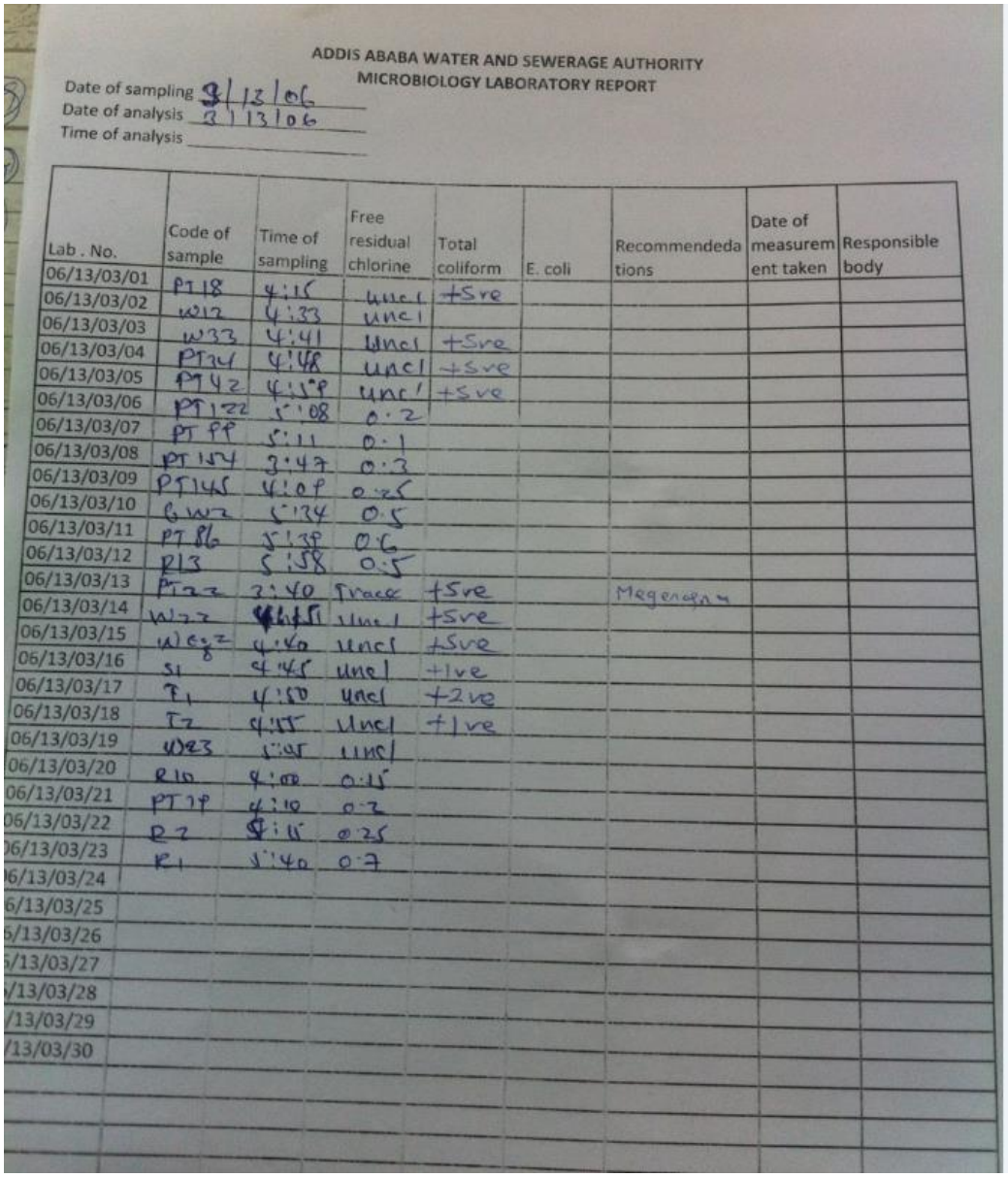
ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 4-13-2006
Date of analysis 4-13-2006
Time of analysis 7:45

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
06/13/04/01	W10	4:10	N:1					
06/13/04/02	W11	4:20	N:1					
06/13/04/03	W9	4:25	Uncl	+Sve				
06/13/04/04	W Mik	4:30	Uncl					
06/13/04/05	K(1)	5:05	Uncl					
06/13/04/06	K(2)	5:40	Uncl					
06/13/04/07	R7	5:55	Trace					
06/13/04/08	PT48	3:30	0.1					
06/13/04/09	PT147	3:35	N:1					
06/13/04/10	PT28	4:15	N:1					
06/13/04/11	PT54	4:20	N:1					
06/13/04/12	PT24	4:30	N:1					
06/13/04/13	PT47	4:40	N:1					
06/13/04/14	R13	9:10	0.75					
06/13/04/15	PT32	3:20	0.35					
06/13/04/16	PT132	3:25	0.8					
06/13/04/17	PT49	3:45	0.7					
06/13/04/18	PT126	4:10	0.15					
06/13/04/19	PT67	4:50	0.4					
06/13/04/20	GW3	4:55	0.5					
06/13/04/21	PT127	4:30	0.4					
06/13/04/22								
06/13/04/23								
06/13/04/24								
06/13/04/25								
06/13/04/26								
06/13/04/27								
06/13/04/28								
06/13/04/29								
06/13/04/30								

R 3

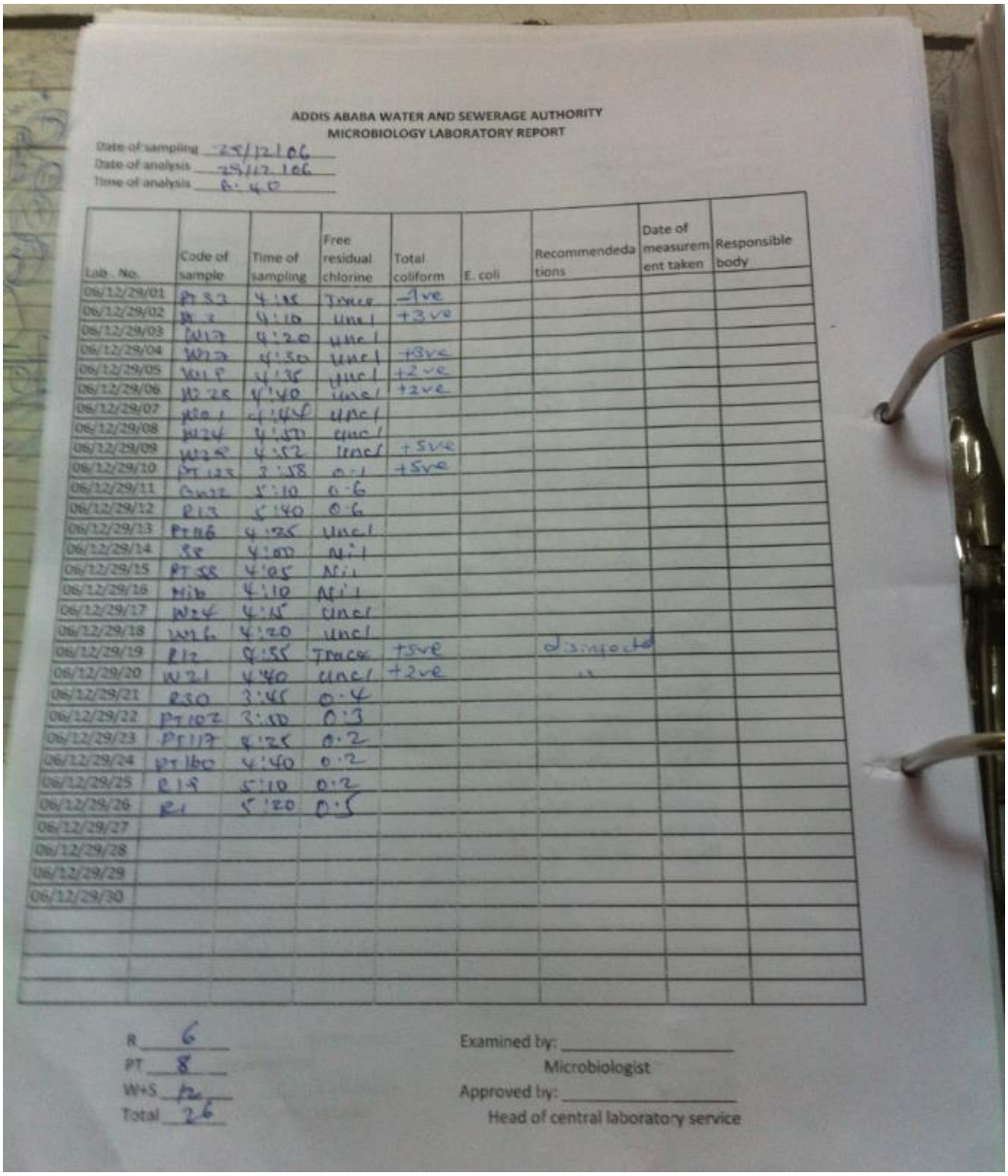
Examined by: _____
Microbiologist



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 3/13/06
Date of analysis 3/13/06
Time of analysis

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
06/13/03/01	PT18	4:15	Uncl	+Sve				
06/13/03/02	W12	4:33	Uncl					
06/13/03/03	W33	4:41	Uncl	+Sve				
06/13/03/04	PT24	4:48	Uncl	+Sve				
06/13/03/05	PT42	4:59	Uncl	+Sve				
06/13/03/06	PT122	5:08	0.2					
06/13/03/07	PT 99	5:11	0.1					
06/13/03/08	PT 154	3:47	0.3					
06/13/03/09	PT145	4:09	0.25					
06/13/03/10	GW2	5:34	0.5					
06/13/03/11	PT86	5:39	0.6					
06/13/03/12	R13	5:58	0.5					
06/13/03/13	PT22	3:40	Trace	+Sve		Megenagna		
06/13/03/14	W22	[illegible]	Uncl	+Sve				
06/13/03/15	W Egg	4:40	Uncl	+Sve				
06/13/03/16	S1	4:45	Uncl	+1ve				
06/13/03/17	T1	4:50	Uncl	+2ve				
06/13/03/18	T2	4:55	Uncl	+1ve				
06/13/03/19	W23	5:05	Uncl					
06/13/03/20	R10	4:00	0.15					
06/13/03/21	PT19	4:10	0.2					
06/13/03/22	R2	4:15	0.25					
06/13/03/23	R1	5:40	0.7					
06/13/03/24								
06/13/03/25								
06/13/03/26								
06/13/03/27								
06/13/03/28								
06/13/03/29								
06/13/03/30								



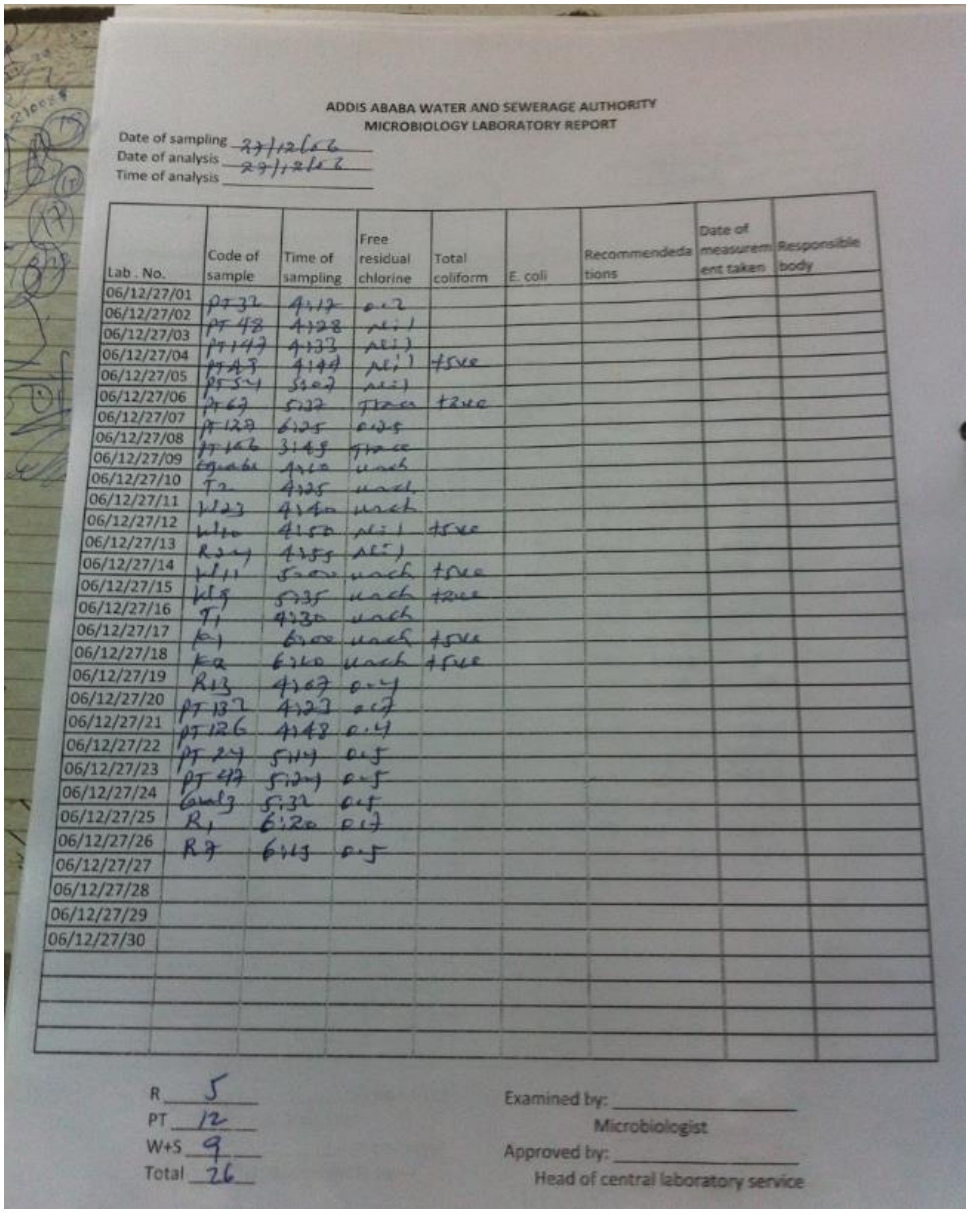
ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 25/12/06
Date of analysis 25/12/06
Time of analysis 8:40

Lab. No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
06/12/29/01	PT 37	4:35	Trace	-ve				
06/12/29/02	W 2	4:10	Uncl	+3ve				
06/12/29/03	W17	4:20	Uncl					
06/12/29/04	W23	4:50	Uncl	+3ve				
06/12/29/05	W11 P	4:35	Uncl	+2ve				
06/12/29/06	W 28	4:40	Uncl	+2ve				
06/12/29/07	W20 1	4:45	Uncl					
06/12/29/08	W24	4:50	Uncl					
06/12/29/09	W25	4:52	Uncl	+5ve				
06/12/29/10	PT 123	3:38	0.1	+5ve				
06/12/29/11	Cm27	5:10	0.6					
06/12/29/12	P13	5:40	0.6					
06/12/29/13	PT46	4:25	Uncl					
06/12/29/14	58	4:00	Nil					
06/12/29/15	PT 58	4:05	Nil					
06/12/29/16	Mib	4:10	Nil					
06/12/29/17	W24	4:15	Uncl					
06/12/29/18	W26	4:20	Uncl					
06/12/29/19	P12	9:55	Trace	+5ve		disinfected		
06/12/29/20	W21	4:40	Uncl	+2ve		"		
06/12/29/21	P30	3:45	0.4					
06/12/29/22	PT102	3:50	0.3					
06/12/29/23	PT117	8:25	0.2					
06/12/29/24	PT160	4:40	0.2					
06/12/29/25	P19	5:10	0.2					
06/12/29/26	P1	5:20	0.5					
06/12/29/27								
06/12/29/28								
06/12/29/29								
06/12/29/30								

R 6
PT 8
W+S 12
Total 26

Examined by: _____
Microbiologist
Approved by: _____
Head of central laboratory service



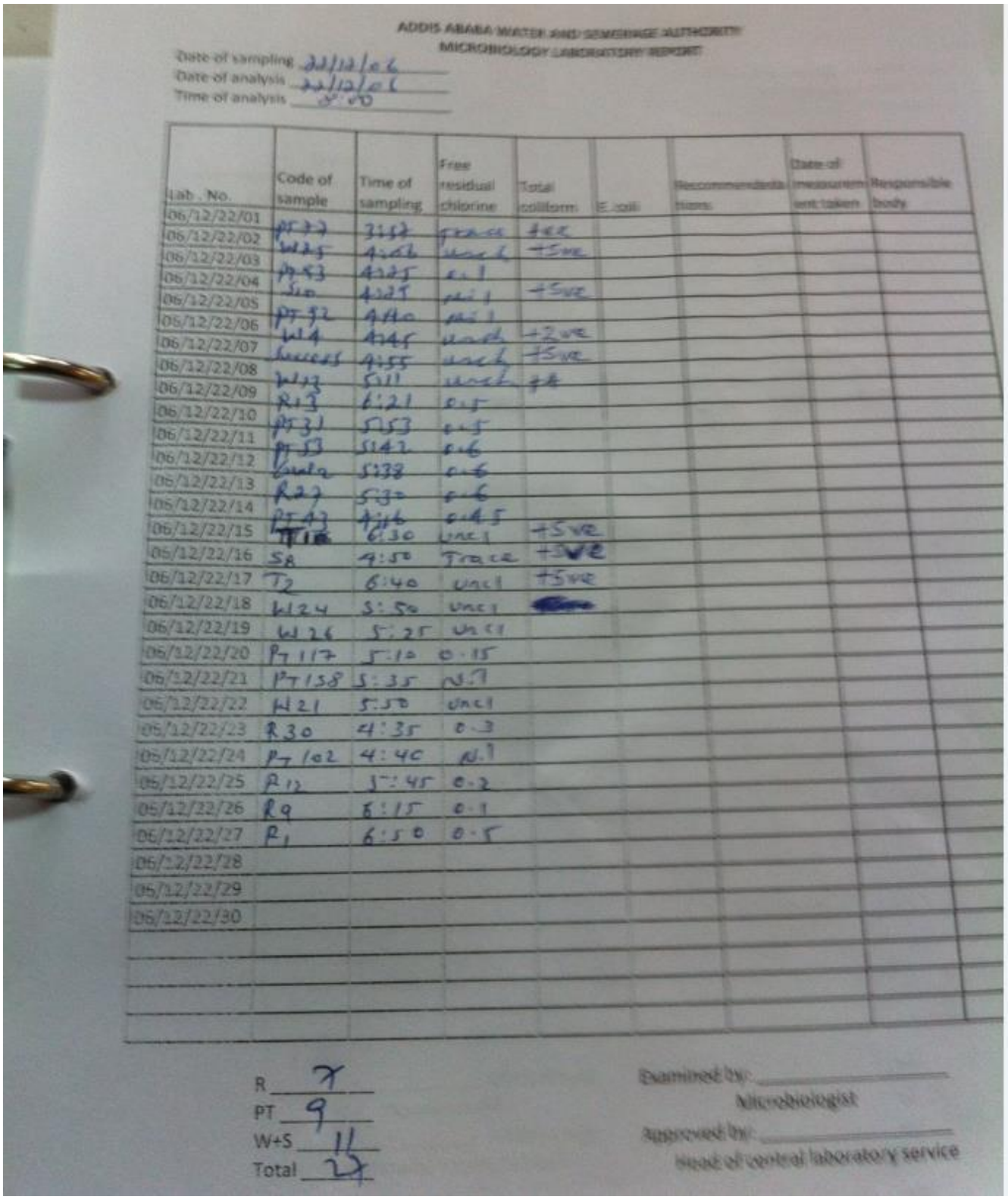
ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 27/12/06
Date of analysis 29/12/06
Time of analysis

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
06/12/27/01	PT 32	4:17	0.2					
06/12/27/02	PT 48	4:28	Nil					
06/12/27/03	PT 147	4:33	Nil					
06/12/27/04	PT 43	4:44	Nil	+ve				
06/12/27/05	PT 54	5:07	Nil					
06/12/27/06	PT 69	5:22	trace	+ve				
06/12/27/07	PT 129	6:25	0.5					
06/12/27/08	PT 146	3:48	trace					
06/12/27/09	Egnabi	4:10	nach					
06/12/27/10	T2	4:25	nach					
06/12/27/11	W23	4:40	nach					
06/12/27/12	W10	4:50	Nil	+ve				
06/12/27/13	R24	4:55	Nil					
06/12/27/14	W11	5:00	nach	+ve				
06/12/27/15	W9	5:35	nach	+ve				
06/12/27/16	T1	4:30	nach					
06/12/27/17	K1	6:00	nach	+ve				
06/12/27/18	K2	6:10	nach	+ve				
06/12/27/19	R13	4:07	0.4					
06/12/27/20	PT 137	4:23	0.7					
06/12/27/21	PT 126	4:48	0.4					
06/12/27/22	PT 24	5:14	0.5					
06/12/27/23	PT 47	5:24	0.5					
06/12/27/24	Gualg	5:32	0.4					
06/12/27/25	R1	6:20	0.4					
06/12/27/26	R7	6:43	0.5					
06/12/27/27								
06/12/27/28								
06/12/27/29								
06/12/27/30								

R 5
PT 12
W+S 9
Total 26

Examined by: _____
Microbiologist
Approved by: _____
Head of central laboratory service



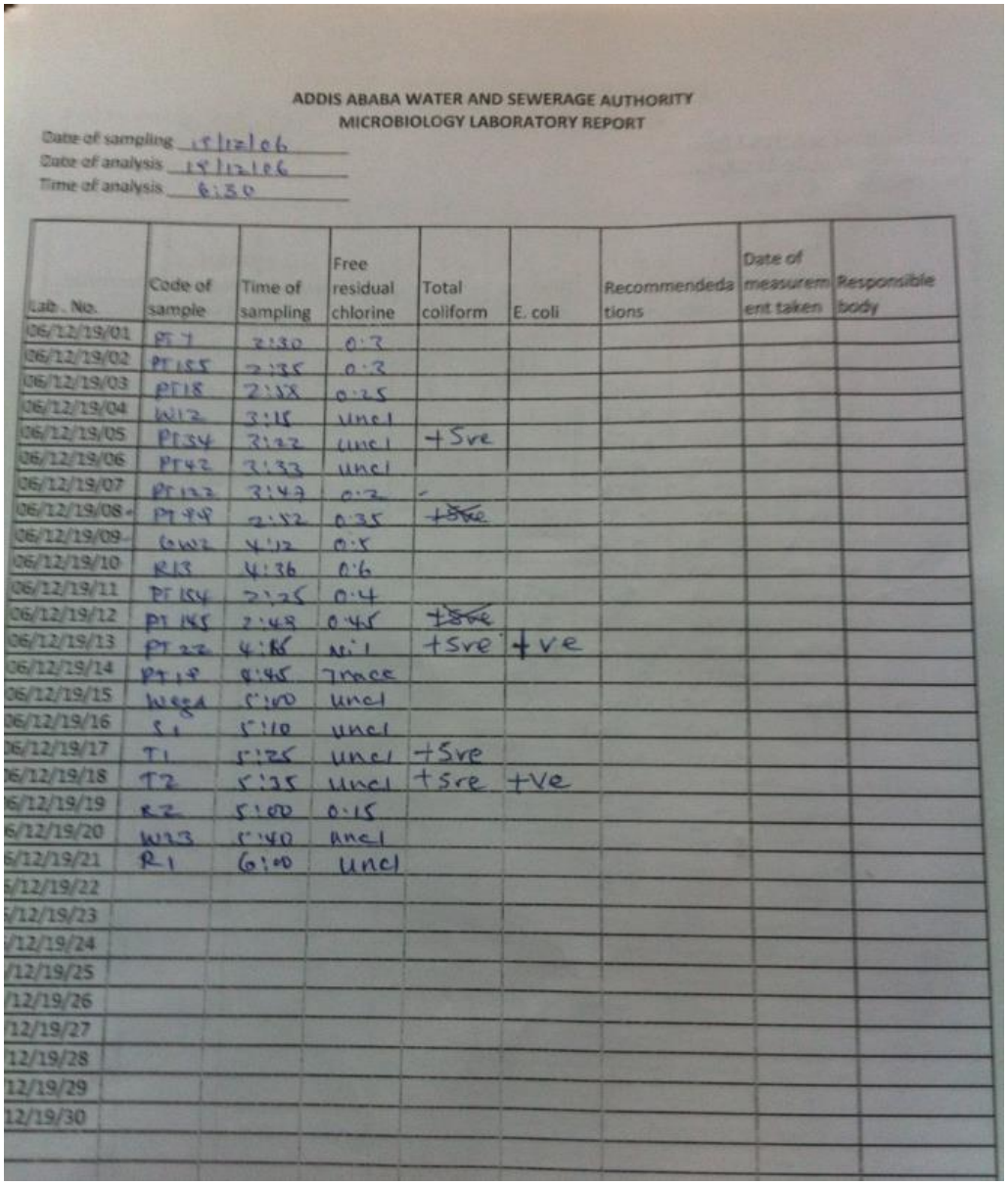
ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 22/12/06
Date of analysis 22/12/06
Time of analysis 5:00

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendations	Date of measurement taken	Responsible body
06/12/22/01	PT 77	3:52	trace	+ve				
06/12/22/02	W25	4:26	nil	+ve				
06/12/22/03	PT 53	4:25	nil					
06/12/22/04	S10	4:25	nil	+ve				
06/12/22/05	PT 92	4:40	nil					
06/12/22/06	W4	4:45	nil	+ve				
06/12/22/07	Success	4:55	nil	+ve				
06/12/22/08	W27	5:11	nil	+ve				
06/12/22/09	R13	6:21	0.5					
06/12/22/10	PT 31	5:53	0.5					
06/12/22/11	PT 53	5:42	0.6					
06/12/22/12	Gulo	5:38	0.6					
06/12/22/13	R27	5:30	0.6					
06/12/22/14	PT 47	4:46	0.45					
06/12/22/15	T10	6:30	Uncl	+ve				
06/12/22/16	SA	4:50	Trace	+ve				
06/12/22/17	T2	6:40	Uncl	+ve				
06/12/22/18	W24	5:50	Uncl	[redacted]				
06/12/22/19	W26	5:25	Uncl					
06/12/22/20	PT 17	5:10	0.15					
06/12/22/21	PT 158	5:35	N.T					
06/12/22/22	H21	5:50	Uncl					
06/12/22/23	R30	4:35	0.3					
06/12/22/24	PT 102	4:40	N.T					
06/12/22/25	R12	5:45	0.2					
06/12/22/26	R9	6:15	0.1					
06/12/22/27	R1	6:50	0.5					
06/12/22/28								
06/12/22/29								
06/12/22/30								

R 7
PT 9
W+S 11
Total 27

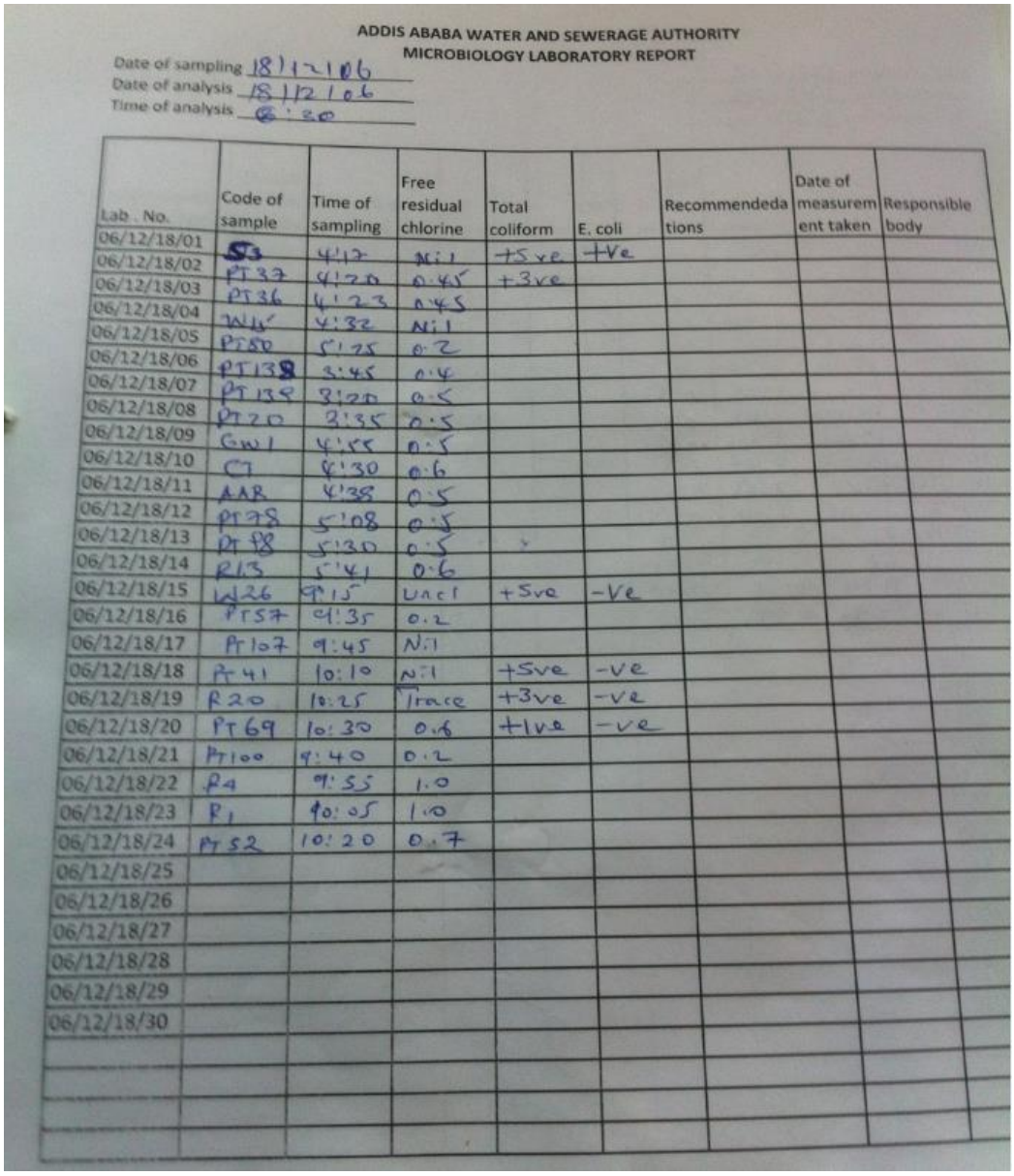
Examined by: _____
Microbiologist
Approved by: _____
Head of central laboratory service



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 15/12/06
Date of analysis 15/12/06
Time of analysis 6:30

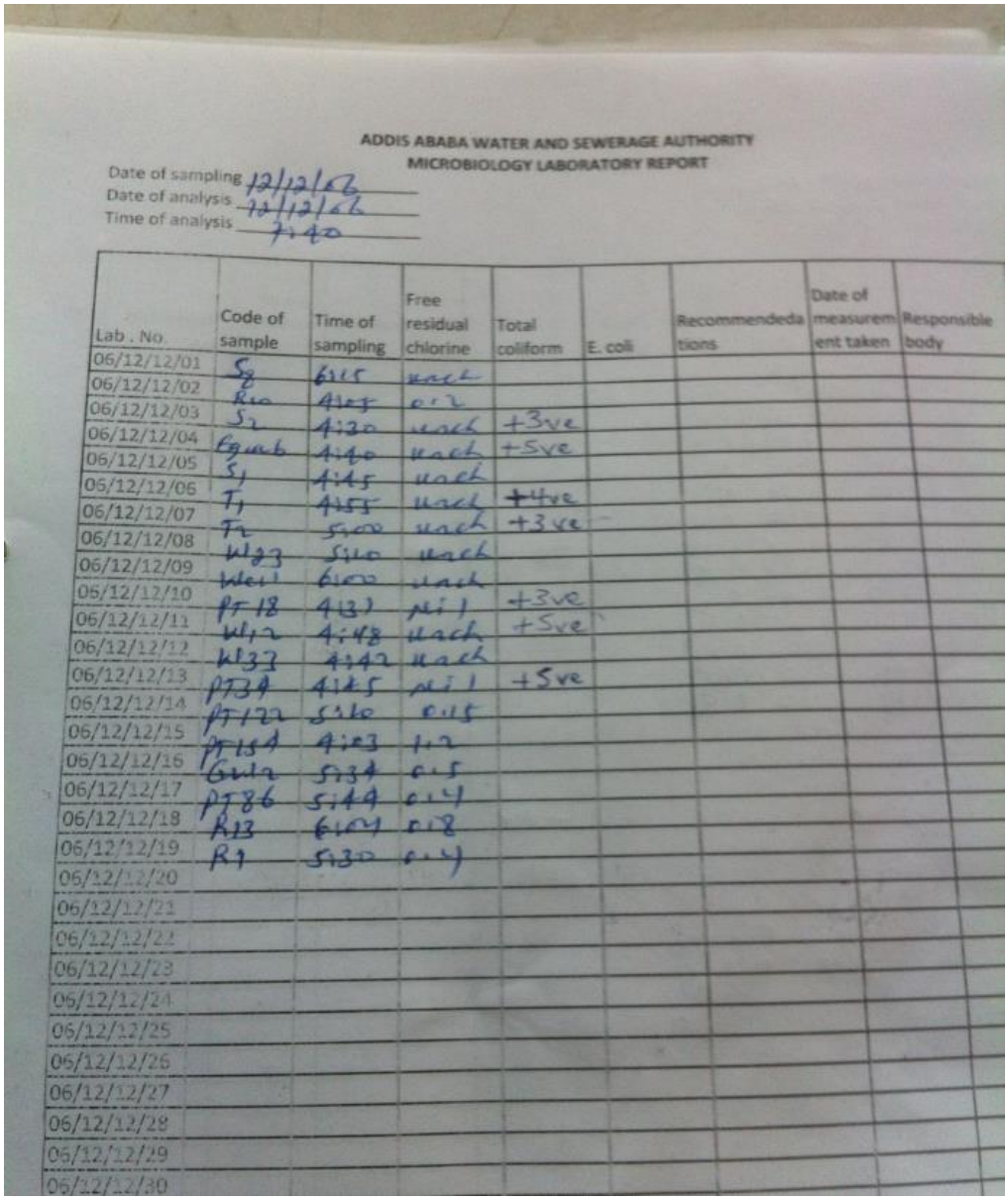
Lab. No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendedations	Date of measurement taken	Responsible body
06/12/19/01	PT 7	2:30	0·3					
06/12/19/02	PT 155	2:35	0·3					
06/12/19/03	PT 18	2:38	0·25					
06/12/19/04	W12	3:15	Uncl					
06/12/19/05	PT 34	3:32	Uncl	+Sve				
06/12/19/06	PT 42	3:33	Uncl					
06/12/19/07	PT 133	3:47	0·3	-				
06/12/19/08	PT 99	2:52	0·35	~~+Sve~~				
06/12/19/09	GW2	4:12	0·5					
06/12/19/10	R13	4:36	0·6					
06/12/19/11	PT 154	2:25	0·4					
06/12/19/12	PT 145	2:48	0·45	~~+Sve~~				
06/12/19/13	PT 22	4:56	Nil	+Sve	+ve			
06/12/19/14	PT 19	8:45	Trace					
06/12/19/15	Wegd	5:00	Uncl					
06/12/19/16	S1	5:10	Uncl					
06/12/19/17	T1	5:25	Uncl	+Sve				
06/12/19/18	T2	5:35	Uncl	+Sve	+Ve			
06/12/19/19	R2	5:00	0·15					
06/12/19/20	W23	5:40	Ancl					
06/12/19/21	R1	6:00	Uncl					
06/12/19/22								
06/12/19/23								
06/12/19/24								
06/12/19/25								
06/12/19/26								
06/12/19/27								
06/12/19/28								
06/12/19/29								
06/12/19/30								



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 18/12/06
Date of analysis 18/12/06
Time of analysis 6:30

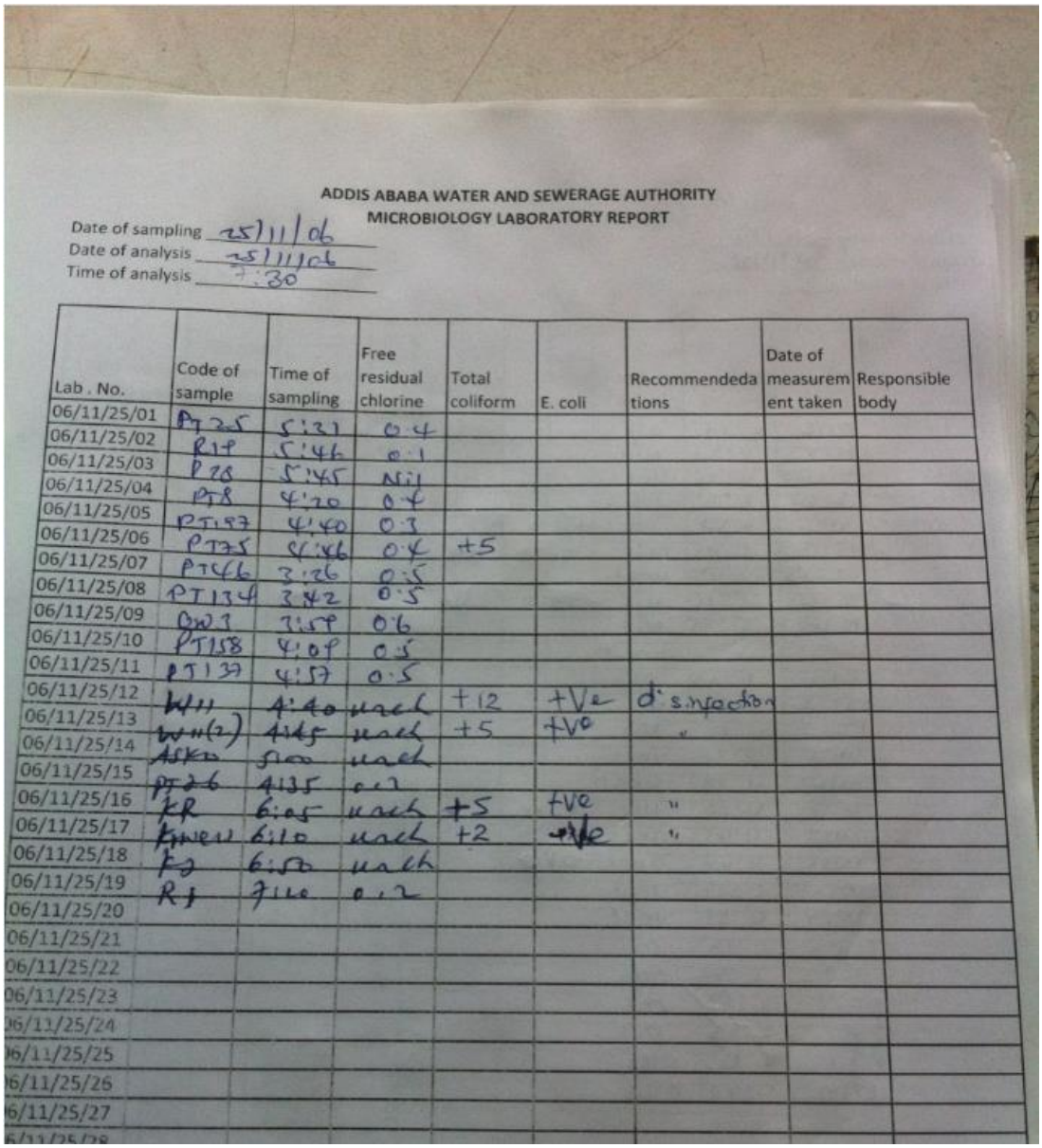
Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
06/12/18/01	S3	4:17	Nil	+5 ve	+Ve			
06/12/18/02	PT37	4:20	0.45	+3ve				
06/12/18/03	PT36	4:23	0.45					
06/12/18/04	W4	4:32	Nil					
06/12/18/05	PT50	5:25	0.2					
06/12/18/06	PT138	3:45	0.4					
06/12/18/07	PT139	3:20	0.5					
06/12/18/08	PT20	3:35	0.5					
06/12/18/09	GW1	4:55	0.5					
06/12/18/10	C7	8:30	0.6					
06/12/18/11	AAB	4:38	0.5					
06/12/18/12	PT78	5:08	0.5					
06/12/18/13	PT 98	5:30	0.5					
06/12/18/14	R13	5:41	0.6					
06/12/18/15	W26	9:15	Uncl	+5ve	-Ve			
06/12/18/16	PT57	9:35	0.2					
06/12/18/17	PT107	9:45	Nil					
06/12/18/18	PT41	10:10	Nil	+5ve	-ve			
06/12/18/19	R20	10:25	Trace	+3ve	-ve			
06/12/18/20	PT69	10:30	0.6	+1ve	-ve			
06/12/18/21	PT100	9:40	0.2					
06/12/18/22	R4	9:55	1.0					
06/12/18/23	R1	10:05	1.0					
06/12/18/24	PT52	10:20	0.7					
06/12/18/25								
06/12/18/26								
06/12/18/27								
06/12/18/28								
06/12/18/29								
06/12/18/30								



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 12/12/06
Date of analysis 12/12/06
Time of analysis 7:40

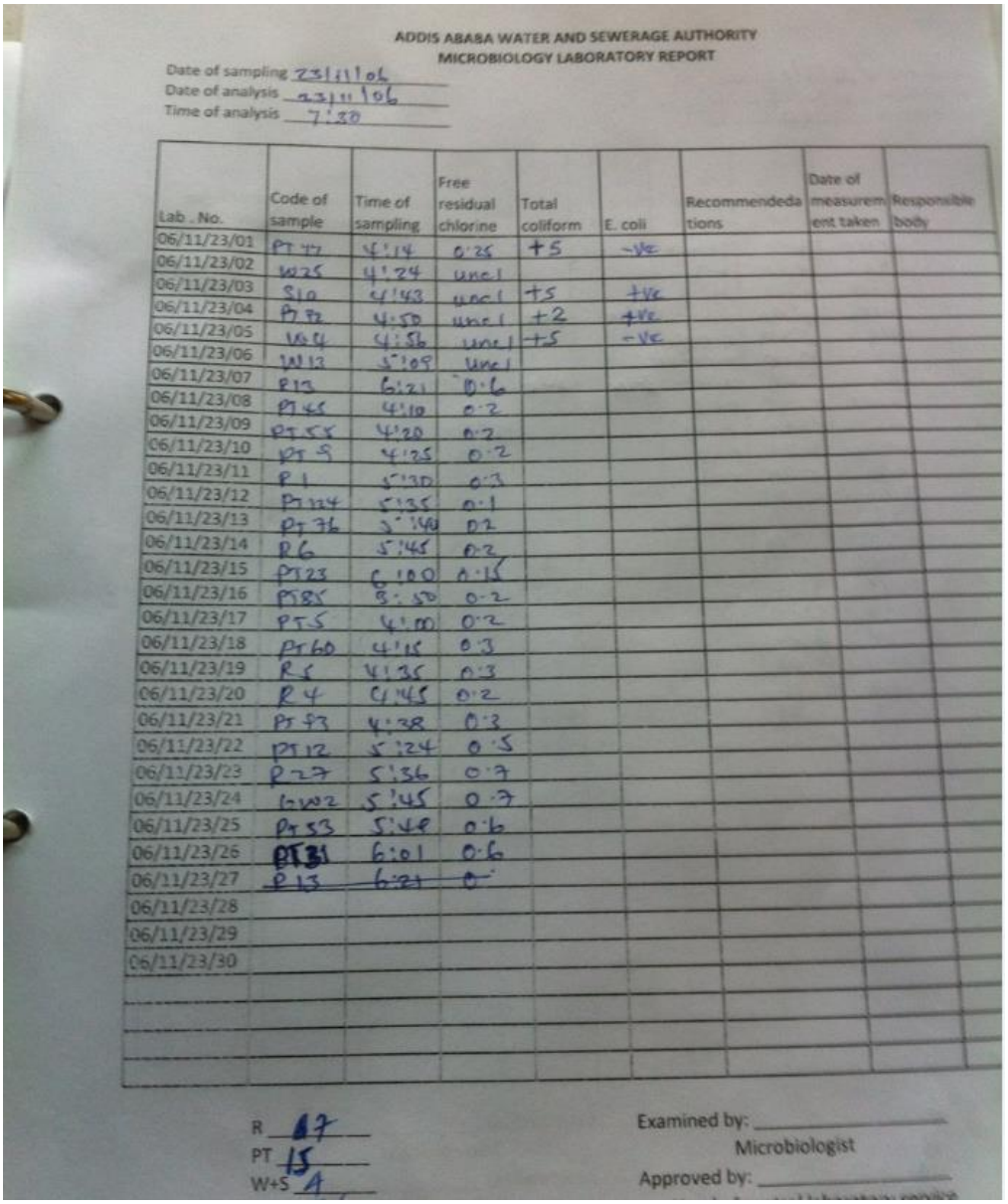
Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendedations	Date of measurement taken	Responsible body
06/12/12/01	S8	6:15	nack					
06/12/12/02	R10	4:05	0.2					
06/12/12/03	S2	4:30	nack	+3ve				
06/12/12/04	Egumb	4:40	nack	+5ve				
06/12/12/05	S1	4:45	nack					
06/12/12/06	T1	4:55	nack	+4ve				
06/12/12/07	T2	5:00	nack	+3ve				
06/12/12/08	W23	5:10	nack					
06/12/12/09	Well	6:00	nack					
06/12/12/10	PT 18	4:30	Nil	+3ve				
06/12/12/11	W12	4:48	nack	+5ve				
06/12/12/12	W33	4:42	nack					
06/12/12/13	PT34	4:25	Nil	+5ve				
06/12/12/14	PT122	5:10	0.15					
06/12/12/15	PT154	4:03	1.2					
06/12/12/16	Gw12	5:34	0.5					
06/12/12/17	PT86	5:44	0.4					
06/12/12/18	R13	6:04	0.8					
06/12/12/19	R1	5:30	0.4					
06/12/12/20								
06/12/12/21								
06/12/12/22								
06/12/12/23								
06/12/12/24								
06/12/12/25								
06/12/12/26								
06/12/12/27								
06/12/12/28								
06/12/12/29								
06/12/12/30								



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 25/11/06
Date of analysis 25/11/06
Time of analysis 7:30

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendedations	Date of measurement taken	Responsible body
06/11/25/01	PT25	5:31	0.4					
06/11/25/02	R1P	5:46	0.1					
06/11/25/03	P28	5:45	Nil					
06/11/25/04	PT8	4:20	0.4					
06/11/25/05	PT197	4:40	0.3					
06/11/25/06	PT75	4:46	0.4	+5				
06/11/25/07	PT46	3:26	0.5					
06/11/25/08	PT134	3:42	0.5					
06/11/25/09	QW3	7:59	0.6					
06/11/25/10	PT158	4:04	0.5					
06/11/25/11	PT137	4:57	0.5					
06/11/25/12	WH	4:40	nack	+12	+Ve	disinfection		
06/11/25/13	WH(2)	4:45	nack	+5	+Ve	"		
06/11/25/14	ASKO	5:00	nack					
06/11/25/15	PT26	4:35	nil					
06/11/25/16	KR	6:05	nack	+5	+Ve	"		
06/11/25/17	KNEW	6:10	nack	+2	+Ve	"		
06/11/25/18	K3	6:50	nack					
06/11/25/19	R1	7:10	0.2					
06/11/25/20								
06/11/25/21								
06/11/25/22								
06/11/25/23								
06/11/25/24								
06/11/25/25								
06/11/25/26								
06/11/25/27								
06/11/25/28								



ADDIS ABABA WATER AND SEWERAGE AUTHORITY
MICROBIOLOGY LABORATORY REPORT

Date of sampling 23/11/06
Date of analysis 23/11/06
Time of analysis 7:30

Lab . No.	Code of sample	Time of sampling	Free residual chlorine	Total coliform	E. coli	Recommendeda tions	Date of measurem ent taken	Responsible body
06/11/23/01	PT 47	4:14	0.25	+5	-ve			
06/11/23/02	W25	4:24	Unc l					
06/11/23/03	S10	4:43	Unc l	+5	+ve			
06/11/23/04	PT 82	4:50	Unc l	+2	+ve			
06/11/23/05	W4	4:56	Unc l	+5	-ve			
06/11/23/06	W13	5:09	Unc l					
06/11/23/07	R13	6:21	0.6					
06/11/23/08	PT 45	4:10	0.2					
06/11/23/09	PT 58	4:20	0.2					
06/11/23/10	PT 9	4:25	0.2					
06/11/23/11	R 1	5:30	0.3					
06/11/23/12	PT 124	5:35	0.1					
06/11/23/13	PT 76	5:40	0.2					
06/11/23/14	R6	5:45	0.2					
06/11/23/15	PT 23	6:00	0.15					
06/11/23/16	PT 85	5:50	0.2					
06/11/23/17	PT 5	4:00	0.2					
06/11/23/18	PT 60	4:15	0.3					
06/11/23/19	R 5	4:35	0.3					
06/11/23/20	R 4	4:45	0.2					
06/11/23/21	PT 53	4:38	0.3					
06/11/23/22	PT 12	5:24	0.5					
06/11/23/23	R 27	5:36	0.7					
06/11/23/24	W02	5:45	0.7					
06/11/23/25	PT 53	5:49	0.6					
06/11/23/26	PT 31	6:01	0.6					
06/11/23/27	R 13	6:21	0.					
06/11/23/28								
06/11/23/29								
06/11/23/30								

R 17
PT 15
W+S 4

Examined by: _____
Microbiologist
Approved by: _____